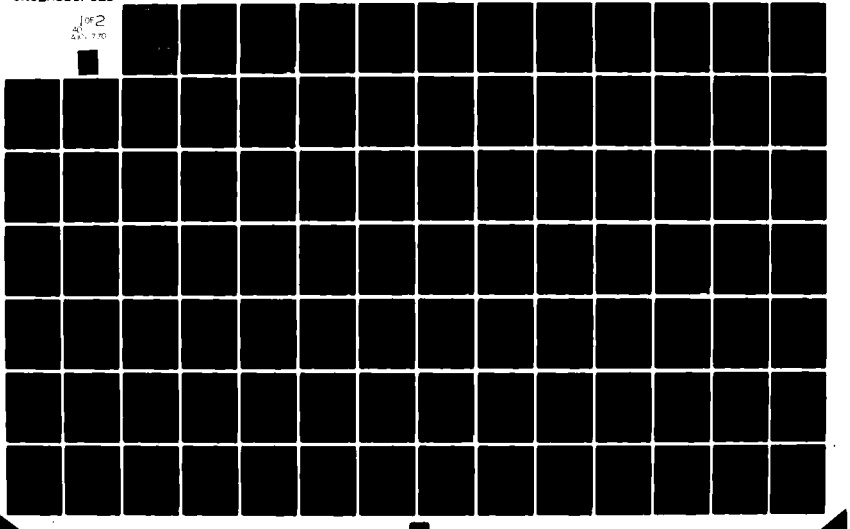

LEVEL II

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Annual Report on Electronics Research at The University of Texas at Austin

No. 28

For the period April 1, 1980 through March 31, 1981

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620—77—C—0101

May 15, 1981

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712

ANNUAL REPORT ON ELECTRONICS RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN No. 28 Electronics Research Center May 15, 1981

The Electronics Research Center at The University of Texas at Austin consists of interdisciplinary laboratories in which graduate faculty members, Master and PhD candidates from numerous academic disciplines conduct research. The disciplines represented in this report include information electronics, solid state electronics, quantum electronics, and electromagnetics.

The research summarized in this report was supported by the Department of Defense's JOINT SERVICES ELECTRONICS PROGRAM (U.S. Army, U.S. Navy, and the U.S. Air Force) through the Research Contract AFOSR F49620-77-C-0101. This program is monitored by the Department of Defense's JSEP Technical Coordinating Committee consisting of representatives from the U.S. Army Research Office, Office of Naval Research and the U.S. Air Force Office of Scientific Research.

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Submitted by Edward J. Powers
on behalf of the faculty and staff
of the Electronics Research Center

15 May ~~15~~ 1981

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ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
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AD-A101 761

ABSTRACT

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation and (2) electronic multi-dimensional signal processing.

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport and (2) spectroscopic studies of metal/semiconductor and metal/metal oxide interfaces are described.

In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, and (3) collective effects in nonlinear optical interactions.

In the Electromagnetics area progress in guided-wave devices for the far infrared-mm wave spectrum is summarized.

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*Denotes persons who have contributed to JSEP projects, but who have not been paid out of JSEP funds (e.g., students on fellowships).

PERSONNEL AND RESEARCH AREAS

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Rudolph Arthur Montgelas, EE, M.S., August 1980, "Evidence for a Waveguide in the Surface Layer of Polished Lithium Tantalate".

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Wayne William Schwiesow, EE, M.S., December 1980, "Coherent Coupling Effects in Vanadium Dioxide".

Sudhakar Yalamanchili, EE, M.S., December 1980, "Differencing Operations for the Segmentation of Moving Objects in Dynamic Scenes".

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Stillwater, Oklahoma
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J.M. White, "Photoassisted Catalysis Using TiO_2 Substrates."

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Virginia Beach, Virginia
May 19-20, 1980

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Implications of Occlusion on Motion
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J.L. Erskine, "Surface States and the Photoelectron Spin Polarization of Ni (100)."

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Rice University
Houston, Texas
June 6, 1980

J.L. Erskine, "Probing Surface Electronic Structure Using Angle Resolved Photoelectron Emission Spectroscopy."

Tamkang Chair Lectures
Tamkang College
Tamsui, Taipei, Taiwan
June 16-18, 1980

J.M. White, "Kinetic Studies of CO Oxidation over Transition Metals."

J.M. White, "The Surface Chemistry of Ruthenium."

J.M. White, "Electron Spectroscopy and its Applications."

National Taiwan University
Taipei, Taiwan
June 17, 1980

J.M. White, "Kinetic Studies of Carbon Monoxide Oxidation over Transition Metals."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

U.S. Army Missile Research
and Development Command
Redstone Arsenal, Alabama
June 17, 1980

*E.J. Powers, "Applications of Digital Bispectral Analysis to Nonlinear Wave Fluctuation Data."

Tsing Hua University
Taiwan
June 19, 1980

*J.M. White, "The Surface Chemistry of Ruthenium."

NATO Advanced Study Institute
on Stochastic Systems
June 20, 1980

M. Hazewinkel and S.I. Marcus, "On Lie Algebras and Nonlinear Estimation."

Optical Society of America Topical
Meeting on Picosecond Phenomena
Falmouth, Massachusetts
June 20, 1980

*M.F. Becker, R.M. Walser, J.G. Ambrose, and D.Y. Sheng, "Picosecond 1.06 Micron Laser-Induced Amorphous Phases in Thin Single-Crystal Silicon Membranes."

NATO Advanced Study Institute
on Stochastic Systems
Les Arcs, France
June 25, 1980
June 26, 1980 (Two lectures)

S.I. Marcus, "An Introduction to Nonlinear Filtering."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

National Cheng Kung University
Taiwan
June 27, 1980

*J.M. White, "Electron Spectroscopy and its Applications."

NATO Advanced Study Institute
on Digital Image Processing
and Analysis
Bonas, France
June 1980

J.K. Aggarwal and W. Martin, "Tracking of Curvilinear Figures."

J.K. Aggarwal and W. Martin, "Motion and Image Analysis."

The 7th International Congress
in Catalysis
Tokyo, Japan
July 1, 1980

J.M. White, "Photoassisted Catalysis Using Platinized Titania."

Gordon Conference on Electron
Charge Densities
Plymouth, New Hampshire
July 1-4, 1980

M. Fink, "Electron Charge Densities in Small Molecules Derived from Electron Diffraction Results."

NATO Advanced Study Institute
on Stochastic Systems
Les Arcs, France
July 3, 1980

*S.I. Marcus, "Modeling and Approximation of Stochastic Differential Equations Driven by Semimartingales."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

Research Institute for Catalysis
Sapporo, Japan
July 7, 1980

*J.M. White, "Chemisorption on Ru(001)."

Twenty-Third Midwest Symposium on Circuits and Systems
Toledo, Ohio
August 4-5, 1980

*D.R. Halverson and G.L. Wise, "Some Results on Asymptotic Memoryless Detection in Strong Mixing Noise."

Joint Automatic Control Conference
San Francisco, California
August 14, 1980

*M. Hazewinkel, C.-H. Liu and S.I. Marcus, "Some Examples of Lie Algebras in Nonlinear Estimation."

XVth International Congress of Theoretical and Applied Mechanics,
Toronto, Canada
August 17-23, 1980

R.W. Miksad, F.L. Jones, Y.C. Kim, E.J. Powers and L. Khadra, "Experiments on Spectral Broadening During Transition to Turbulence."

Hughes Aircraft Company
Project Meeting
Torrance, California
August 21, 1980

T. Itoh, "Millimeter Wave Research at the University of Texas."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

International URSI
Electromagnetic Symposium
Munich, W. Germany
August 26-29, 1980

T. Itoh and L.P. Schmidt, "Characteristics of a Generalized Fin-Line for Millimeter-wave Integrated Circuits."

National ACS Meeting
Las Vegas, Nevada
August 27, 1980

J.M. White, "Transient Low Pressure Studies of Catalytic Carbon Monoxide Oxidation."

AEI Limited
Seminar
Lincoln, England
October 3, 1980

T. Itoh, "Dielectric Millimeter-wave Circuits."

5th International Symposium on Infrared
and Millimeter Wave
Würzburg, W. Germany
October 6-10, 1980

I. Awai and T. Itoh, "Multilayered Open Dielectric Waveguide with a Gyrotropic Layer."

EXPOCHEM 80
Houston, Texas
October 8, 1980

*J.M. White, "Electron Spectroscopy as a Tool for Studying Chemisorption and Catalytic Reactions on Ru(001)."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

Eighteenth Annual Allerton Conference
on Communication, Control, and Computing
Monticello, Illinois
October 8-10, 1980

*D.R. Halverson and G.L. Wise,
"On the Performance of a Modified
Sign Detector for Strong Mixing Noise."

J.A. Bucklew and G.L. Wise,
"A Note on Multidimensional
Asymptotic Quantization Theory."

*F. Kuhlmann and G.L. Wise,
"On Spectral Characteristics of
Median Filtered Independent Data."

Workshop on Modern Millimeter Wave Systems
Estes Park, Colorado
October 22-24, 1980

*T. Itoh, "Millimeter Waveguiding Structures."

Optical Society of America Annual Meeting
Chicago, Illinois
October 1980

M.F. Becker, J.G. Mauger, and Y. Twu,
"Raman Enhanced Third-Harmonic Generation
in CD_4."

22nd Annual Meeting of the Division of Plasma
Physics
San Diego. California
November 10-14, 1980

T. Kochanski, R.D. Bengtson, G. Kochanski,
Y.C. Kim, L. Khadra, and E.J. Powers,
"Observation of Mirnov Type Oscillations
on PRETEXT with Magnetic and Photon Detectors."

22nd Annual Meeting of the Division of Plasma Physics
San Diego, California
November 10-14, 1980
(continued)

Y.C. Kim, L. Khadra, E.J. Powers, T.P. Kochanski, and R.D. Bengtson, "Spectral Characteristics of M.H.D Fluctuations on PRETEXT."

C.M. Surko, R.E. Slusher, R.D. Bengtson, S.E. Mahajan, M.E. Oakes, T.E. Evans, Y.M. Li, and E.J. Powers, "An Experiment to Study Kinetic Alfvén Waves Using CO_2 Laser Scattering."

J.M. Beall, Y.C. Kim, and E.J. Powers, "Experimental Study of Drift Wave Turbulence."

Materials Research Society
1980 Annual Meeting
Boston, Massachusetts
November 18, 1980

R.M. Walser, "Heterogeneous Nucleation of Spatially Coherent Damage Structures in Crystalline Silicon with Picosecond 1.06 Micron and 0.53 Micron Laser Pulses."

33rd Annual Meeting of the Division of Fluid Dynamics
Ithaca, New York
November 23, 1980

R.W. Miksad, F.L. Jones, Y.C. Kim, E.J. Powers, and L. Khadra, "Experiments on Wave-Wave Interactions During Transition to Turbulence."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

University of Miami
Miami, Florida
November 24, 1980

J.A. Schreifels. S.-K. Shi and J.M. White, "Temperature Dependence of Electron Beam Damage During the Titration of Adsorbed Oxygen with Hydrogen on a Ru(001) Surface."

Materials Research Society Annual Meeting
Boston, Massachusetts
November 1980

*R.M. Walser, M.F. Becker, J.G. Ambrose, and D.Y. Sheng, "Heterogeneous Nucleation of Spatially Coherent Damage Structures in Crystalline Silicon with Picosecond 1.06μm and 0.53μm Laser Pulses."

University of Southern California
EE Seminar
Los Angeles, California
December 3, 1980

*T. Itoh, "Microwave and Millimeter-Wave Research at University of Texas."

Colloquium-Presented to the Physics Department
Texas A&M University
College Station, Texas
December 7, 1980

J.W. Keto, "Two Photon Spectroscopy of Xenon."

5th International Conference
on Pattern Recognition
Miami Beach, Florida
December 1980

J.K. Aggarwal and J. Webb, "Observing Jointed Objects."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

19th IEEE Conference on Decision and Control
Albuquerque, New Mexico
December 10, 1980

*J.K. Aggarwal and Nian-Chyi Huang,
"Time-Varying Digital Signal Processing."

5th International Conference
on Pattern Recognition
Miami Beach, Florida
December 1980

J.K. Aggarwal, W. Martin, and S. Yalamanchili,
"Image Differencing for Moving Object
Extraction in Dynamic Scenes."

Physical Electronics Industries
Eden Prairie, Minnesota
February 4, 1981

J.M. White, "XPS Studies of the
Oxidation of Cerium."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

Arizona State University
Tempe, Arizona
February 10, 1981
(condensed matter seminars)

*J.L. Erskine, "Magnetic Dead Layers and the Surface Electronic Structure of Nickel."

University of Arizona
Tucson, Arizona
February 13, 1981
(condensed matter seminars)

*J.L. Erskine, "Magnetic Dead Layers and the Surface Electronic Structure of Nickel."

Colloquium-Presented to the Physics Department
Texas A&M University
College Station, Texas
February 13, 1981

L. Frommhold, "Intermolecular Spectroscopy."

International Solid State Circuit Conference
Panel Session
New York, New York
February 18-20, 1981

*T. Itoh, "Distributed Millimeter-Wave Components."

Dept. of Electrical Engineering and
Computer Science Seminar
Polytechnic Institute of New York
Brooklyn, New York
February 20, 1981

*T. Itoh, "Microwave and Millimeter-Wave Research at University of Texas."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

University of Missouri
St. Louis, Missouri
February 29, 1981

J.A. Schreifel, S.-K. Shi, and J.M. White, "Temperature Dependence of Electron Beam Damage During the Titration of Adsorbed Oxygen with Hydrogen on a Ru(001) Surface."

Cornell University
Surface Physics/Condensed Matter Seminar
Ithaca, New York
March 6, 1981

*J.L. Erskine, "Surface Magnetic Properties of Magnetic Metals."

1981 Conference on Information Sciences and Systems
Baltimore, Maryland
March 25-27, 1981

*D.R. Halverson, and G.L. Wise, "On the Performance of Approximately Optimal Memoryless Detectors for Signals in Dependent Noise."

F. Kuhlmann, J.A. Bucklew, and G.L. Wise, "Nonuniform Quantization and Transmission of Generalized Gaussian Signals over Noisy Channels."

American Cyanamid Co.
Stanford, Connecticut
March 30, 1981

Bor-Her Chen, "Photoassisted Water Decomposition by Pt-TiO_2."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

IEEE International Conference
on Acoustics, Speech, and Signal Processing
Atlanta, Georgia
March 30-April 1, 1981

*J.K. Aggarwal, and Nian-Chyi Huang,
"Spectral Modifications using Linear
Shift-Varying Digital Filters."

IEEE International Conference
on Acoustics, Speech, and Signal Processing
Atlanta, Georgia
March 30-April 1, 1981

*Hyokang Chang, and J.K. Aggarwal
"Implementation of Two-Dimensional
Semicausal Recursive Digital Filters."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

CONFERENCE PROCEEDINGS

*E.J. Powers, Y.C. Kim, and J.M. Beall, "Nonlinear Wave Coupling and Bispectral Analysis," Proceedings of the International Conference on Plasma Physics, Nagoya, Japan, April 7-11, 1980.

E.J. Powers, Y.C. Kim, J.Y. Hong, J.R. Roth, and W.M. Krawczonek, "Radially Inward Fluctuation-Induced Transport in a Bumpy Torus Plasma," Proceedings of the International Conference on Plasma Physics, Nagoya, Japan, April 7-11, 1980.

G.L. Wise, "Recent Results Concerning the Effects of Nonlinearities on Random Inputs," Proceedings of the Twelfth Southeastern Symposium on System Theory, Virginia Beach, Virginia, pp. 290-294, May 19-20, 1980.

J.K. Aggarwal and W.N. Martin, "The Implications of Occlusion on Motion Analysis in Dynamic Scenes," Proceedings of Pattern Recognition on Practice Conference, Amsterdam, Holland, May, 1980.

K. Araki, B.S. Song and T. Itoh, "Nonreciprocal Effects in Open Dielectric Waveguide with Grating Structures," International Microwave Symposium Digest, Washington, D.C., May 1980.

L.P. Schmidt, T. Itoh and J. Hofmann, "Characteristics of Unilateral Fin-Line Structures with Arbitrarily Located Slots," International Microwave Symposium Digest, Washington, D.C., May 1980.

T. Itoh and B. Adelseck, "Trapped Image Guide for Millimeter-Wave Circuits," International Microwave Symposium Digest, Washington, D.C., May 1980.

R.M. Walser, M.F. Becker, D.Y. Sheng, and J.G. Ambrose, "Picosecond 1.06μm Laser-Induced Amorphous Phases in Thin Single Crystal Silicon Membranes," Picosecond Phenomena, Falmouth Massachusetts, June 1980.

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*Funded entirely or in part by the Joint Services Electronics Program.

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T.Itoh and B. Adelseck, "Trapped Image Guide Leaky-Wave Antennas for Millimeter-Wave Applications," IEEE/AP-S International Symposium Digest, Quebec, Canada, June 1980.

*D.R. Halverson and G.L. Wise, "Some Results on Asymptotic Memoryless Detection in Strong Mixing Noise," Proceedings of the 23rd Midwest Symposium on Circuits and Systems, Toledo, Ohio, August 4-5, 1980.

*M. Hazewinkel, C.-H. Liu, and S.I. Marcus, "Some Examples of Lie Algebras in Nonlinear Estimation," Proceedings of Joint Automatic Control Conference, San Francisco, California, August 14, 1980.

T. Itoh and L.P. Schmidt, "Characteristics of a Generalized Fin-Line for Millimeter-Wave Integrated Circuits," International URSI Symposium Digest, Munich, W. Germany, August 1980.

L.W. Frommhold, and M.H. Proffitt, "Collision-Induced Light Scattering and Diatom Polarizabilities-An Overview," International Conference of Collision-Induced Phenomena, Florence,Italy, September 2-6, 1980.

L.W. Frommhold and M.H. Proffitt, "New Measurements of Collision-Induced Scattering in the Rare Gases," International Conference of Collision-Induced Phenomena, Florence, Italy, September 2-6, 1980.

I. Awai and T. Itoh, "Multilayered Open Dielectric Waveguide with a Gyrotropic Layer," 5th International Symposium on Infrared and Millimeter Waves, Würzburg, W. Germany, October 6-10, 1980.

*D.R. Halverson and G.L. Wise, "On the Performanace of a Modified Sign Detector for Strong Mixing Noise," Proceedings of the Eighteenth Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, October 8-10, 1980.

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*F. Kuhlmann and G.L. Wise, "On Spectral Characteristics of Median Filtered Independent Data," Proceedings of the Eighteenth Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, October 8-10, 1980.

A. Bucklew, and G.L. Wise, "A Note on Multidimensional Asymptotic Quantization Theory," Proceedings of the Eighteenth Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, October 8-10, 1980.

*J.K. Aggarwal and Nian-Chyi Huang,"Time-Varying Digital Signal Processing," Proceedings of the 19th IEEE Conference on Decision and Control, pp. 586-587, Albuquerque, New Mexico, December 10, 1980.

S.I. Marcus, "Modeling of Nonlinear Systems Driven by Semimartingales with Application to Nonlinear Filtering," IEEE Conference on Decision and Control , Albuquerque, New Mexico, December, 10, 1980.

*J.C. Krainak, J.C. Speyer, and S.I. Marcus, "Static Decentralized Team Problems: Sufficient Conditions, Algorithms, and the Exponential Cost Criteron," Proceedings of the 19th IEEE Conference on Decision and Control, Albuquerque, New Mexico , December 10, 1980, pp. 1191-1196.

*K. Hsu and S.I. Marcus, "Decentralized Control of Finite State Markov Processes," Proceedings of the 19th IEEE Conference on Decision and Control, Albuquerque, New Mexico, pp. 1191-1196, December 10, 1980.

*M. Hazewinkel and S.I. Marcus,"On the Relationship Between Lie Algebras and Nonlinear Estimation," Proceedings of the 19th IEEE Conference on Decision and Control, Albuquerque, New Mexico, December 10, 1980, pp. 60-71.

K. Araki, T. Itoh, and Y. Naito, "Hankel Transform Domain Analysis of Open Circular Microstrip Radiating Structures," IEEE AP-S, International Symposium, Quebec, Canada, June, 1980.

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*F. Kuhlmann, J.A. Bucklew, and G.L. Wise, "Nonuniform Quantization and Transmission of Generalized Gaussian Signals over Noisy Channel," Proceedings of the 1981 Conference on Information Sciences and Systems, Baltimore, Maryland, March 25-27, 1981.

*S.I. Marcus,"Modeling of Nonlinear Systems Driven by Semi-martingales with Applications to Nonlinear Filtering," Proceedings of Johns Hopkins Conference on Information Sciences and Systems, Baltimore, Maryland, March 25-27, 1981.

*Hyokang Chang and J.K. Aggarwal, "Implementation of Two-Dimensional Semicausal Recursive Digital Filters," Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing, Atlanta, Georgia, pp. 995-999, March 30-April 1, 1981.

*J.K. Aggarwal, and Nian-Chyi Huang, "Spectral Modifications using Linear Shift-Varying Digital Filters," Proceedings of IEEE International Conference on Acoustics,Speech, and Signal Processing, Atlanta, Georgia, pp. 73-77, March 30-April 1, 1981.

R.M. Walser,"Heterogeneous Nucleation of Spatially Coherent Damage Structures in Crystalline Silicon with Picosecond 1.06μm and 0.53μm Laser Pulses," Laser-Solid Interactions and Laser Processing, to be published by North-Holland (1981).

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J.K. Aggarwal and J. Webb, "Observing Jointed Objects," Proceedings of the 5th International Conference on Pattern Recognition, Miami Beach, Florida, December 1980, pp. 1246-1250.

*M.F. Becker, G.J. Mauger, and Y. Twu, "Raman Resonance Enhanced Third-Harmonic Generation in CD_4," Abstracts from the Annual Meeting of the Optical Society of America, 1980.

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*M.F. Becker, R.M. Walser, J.G. Ambrose, and D.Y. Sheng, "Picosecond, 1.06 micron Laser-Induced Amorphous Phases in Thin, Single-crystal Silicon Membranes," Abstracts from the Topical Meeting Picosecond Phenomena, Optical Society of America, 1980.

*R.M. Walser, M.F. Becker, J.G. Ambrose, and S.Y. Sheng, "Heterogeneous Nucleation of Spatially Coherent Damage Structures in Crystalline Silicon with Picosecond 1.06μm and 0.53μm Laser Pulses," Abstracts from the Annual Meeting of the Materials Research Society, 1980

J.L. Erskine, "Auger and Photoelectron Emission Study of Xenon on W(001)," Meeting of the American Physical Society Phoenix, Arizona, March 16-20, 1981 contributed paper.

*D.R. Halverson, and G.L. Wise, "On the Performance of Approximately Optimal Memoryless Detectors for Signals in Dependent Noise," Proceedings of the 1981 Conference on Information Sciences and Systems, Baltimore, Maryland, March 25-27, 1981.

I. INFORMATION ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE80-1 NONLINEAR DETECTION AND ESTIMATION

Principal Investigators: Professor S.I. Marcus (471-3256)
Professor T.J. Wagner (471-3181)
Professor G.L. Wise (471-3356)

Research Associate: Don R. Halverson

Graduate Students: E. Abaya, N. Khazenie, F. Kuhlmann and C. Liu

A. OBJECTIVES AND PROGRESS: This research unit is concerned with several aspects of the statistical properties of nonlinear systems. Specifically, the design and analysis of nonlinear estimators, the design of nonlinear systems for signal detection, and the performance of adaptive delta modulators have been investigated.

1. Nonlinear Estimation:

The area of nonlinear state estimation is concerned with the extraction of information about the state of a stochastic system from nonlinear noisy measurements. The state estimate is generated by passing the measurements through a nonlinear system. Optimal state estimators have been derived for very general classes of nonlinear systems, but these are in general infinite dimensional. That is, it is usually not possible to recursively generate the optimal minimum variance estimate (the conditional mean) of the system state given the past observations. The basic objective here is the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time. There are few known cases aside from the linear (Kalman) filtering problem in which the conditional mean (the minimum variance estimate) of the system state given the past observations can be computed recursively in real time with a filter of fixed finite dimension. However, in [1] we have proved that for certain classes of discrete-time and continuous-time systems, described either by a finite Volterra series or by certain types of state-affine realizations, the minimum variance estimator is recursive and of fixed finite dimension. This was accomplished by relating these problems to the homogeneous chaos of Wiener and to orthogonal expansions of Gaussian processes.

In [2], by employing the finite dimensional estimators which we derived in [1], we have for the first time been able to analyze the performance of suboptimal estimators and the tightness of estimation lower bounds for a nonlinear system

by comparison with the optimal estimator. A system for which we can construct the optimal estimator was studied; the optimal estimator, extended Kalman filter (EKF), constant gain extended Kalman filter (CGEKF), best linear estimator (BLE), and Bobrovsky-Zakai lower bound were compared both analytically and via Monte Carlo simulations. The results indicated that the performance of the EKF is virtually as good as that of the optimal estimator, and the Bobrovsky-Zakai lower bound is tight for very high signal-to-noise ratio but is less effective for large values of state and observation noises. As far as suboptimal filter design is concerned, the CGEKF is probably preferable, in most of the cases studied, to the optimal estimator and the EKF, due to its simple computational requirements.

We have begun to consider a new approach, involving the use of Lie algebraic techniques, to nonlinear estimation problems. This approach proceeds by studying the (Zakai) stochastic partial differential equation for an unnormalized conditional density of ρ of the state x given the past observations z:

$$d\rho(t,x) = L_0\rho(t,x)dt + L_1\rho(t,x)dz.$$

The major idea of the approach is that, if L is the Lie algebra generated by $L_0 - \frac{1}{2} L_1^2$ and L_1, and if a recursive finite dimensional estimator for some statistic of the state exists, then there is a Lie algebra homomorphism from L to the Lie algebra F of the finite dimensional filter. The existence of Lie algebra homomorphisms is thus closely related to the existence of finite dimensional recursive filters. An important step in this program has been completed in [3], in which we analyze in detail the Lie algebra L associated with the unnormalized conditional density equation for a particular example of the class of problems solved in [1]. In addition, the Lie algebras associated with the recursively computable conditional moment equations are computed, and the relationships (e.g., homomorphisms) between these Lie algebras are studied. This study provides further evidence that the existence of finite dimensional quotients of L is closely related to the existence of recursive finite dimensional estimators; in fact, this is the first example in which L is an infinite dimensional Lie algebra for which such a study has been carried out. More general classes of nonlinear estimation problems are considered in [4] and [5], where we show for example that the estimation problem for bilinear systems with linear obser-

vations has an algebraic structure similar to that of the example studied in [3]; thus there is hope for being able to derive recursive finite dimensional filters for some conditional statistics of the state in such problems (no such filters are known at present). On the other hand, we also show that for certain classes of nonlinear estimation problems, no conditional statistic of the state can be computed with a finite dimensional filter. This is the first such result in the literature, and it applies for example to a linear system with cubic observations (the cubic sensor problem).

In [6] we have utilized our previous results on stochastic differential equations to design efficient low-order filters for nonlinear estimation problems in which the observation process is a jump process. One case in which such observations arise is in the field of laser communications. We have shown that although the optimal filter is generically n-dimensional for the problem of estimating an n-state Markov process, there are problems in which the optimal filter can be computed with just four sufficient statistics, a considerable saving if n is large.

The research in this area is continuing and has been complemented by Grant AFOSR-79-0025 from the Air Force Office of Scientific Research and Grants ENG 76-11106 and ECS-8022033 from the National Science Foundation.

2. Nonlinear Detection:

We have considered a number of topics within the general area of signal detection theory. Research has been devoted toward both parametric and nonparametric approaches where the underlying processes are non-Gaussian and possess dependency. The memoryless detection of a constant signal in additive m-dependent noise has been considered previously by other researchers. Using the criterion of asymptotic relative efficiency, a necessary and sufficient condition was given for the optimal detector over the class of all Neyman-Pearson optimal "white noise" detectors. The canonical form for this class of detectors is a nonlinearity $g(\cdot)$ followed by an accumulator which is then followed by a comparator. As discussed in [7], however, there are some difficulties in the choice of an m-dependent model for the noise. What is more appealing is a more general model which exploits the expected "decrease" in dependency as samples are more widely separated in time, without specifying absolute statistical independence as required by an m-dependent assumption. A popular choice of such a process is the ϕ-mixing process. In [7] we have extended the previous work to the case where

the noise is ϕ-mixing. Under some mild regularity conditions, we have found that the optimal detector nonlinearity $g(\cdot)$ must satisfy a certain integral equation. This condition requires only second order knowledge of the statistics of the noise, however, in our case the integral equation is of non-standard form. Accordingly, a method for obtaining the solution $g(\cdot)$ has been presented in [7]. One considers solutions $g_m(\cdot)$ to an integral equation which can be manipulated into a standard form and the solution $g_m(\cdot)$ thus obtained through standard Hilbert-Schmidt techniques. We have established conditions for the existence and uniqueness of the optimal nonlinearity $g(\cdot)$, and in this case we have also shown $g_m(N_1) \xrightarrow{m.s.} g(N_1)$, where the (stationary) noise process is $\{N_i\}_{i=1}^{\infty}$. Optimal performance may thus be approached arbitrarily closely through the use of nonlinearities which can be found via standard Hilbert-Schmidt techniques.

Because of the likely employment of one of the nonlinearities $g_m(\cdot)$, we might in practice expect that the resultant detector might only be approximately optimal. In [8] we consider another approximation which has its own advantages. If we approximate the optimal nonlinearity $g(\cdot)$ with a polynomial $p_M(x) = \sum_{i=0}^{M} a_i x^i$, then we can show that the coefficients of the optimal polynomial $p_M(\cdot)$ of degree M may be found via a relatively simple maximization, for which Lagrange multiplier techniques may be employed to yield a system of linear equations. Thus this approach has the advantage of requiring the solution of a system of linear equations rather than an integral equation; moreover, knowledge of joint moments as opposed to joint densities is all that is required. Of course the employment of an approximation to the optimal nonlinearity is of little value unless the performance of the approximation can be made close to optimal, and in [8] conditions for this are established.

The above work deals with the detection of a constant signal. In [9] we extend the approach to the detection of ϕ-mixing noise, where a large amount of dependency is permitted between the signal and noise processes. If the noise is either independent of the signal or is dependent on a finite "window" of the signal (such as the signal-dependent noise induced through reverberation effects), we may obtain the corresponding condition for the optimal nonlinearity $g(\cdot)$ in this general random signal in random noise situation. To be more specific, if the noise $\{N_i\}_{i=1}^{\infty}$ is either independent

of the signal $\{S_i\}_{i=1}^{\infty}$ or related to the signal via a certain type of weak dependence, then we give in [9] necessary and sufficient conditions for the optimality of $g(\cdot)$. In particular these results show that if the signal is independent of the noise and has nonzero mean, then the optimal nonlinearity is the same as in the constant signal case. Solutions to these nonlinear integral equations may be obtained through the approach described in [7].

In [10] we consider an even more general class of processes to model the signal and noise, the class of strong mixing processes. This class includes the ϕ-mixing processes and the validity of such a model is easier to check because of ties to the maximal correlation coefficient. For the case of a strong mixing signal in strong mixing noise with the same kind of dependency as considered in [9], we show in [10] that the optimal nonlinearity is again a solution to the equations obtained in [9]. Letting $g_m(\cdot)$ be defined corresponding to the equations of [9] in the same manner as in [7], it is shown in [10] that if there exists an appropriate nonlinearity $g(\cdot)$ such that $g_m(N_1)-g(N_1)\to 0$ in $L_{2+\delta}$ for some $\delta>0$, then $g(\cdot)$ is optimal. Adopting the more general model thus involves the cost of requiring more than the mean square convergence encountered in the ϕ-mixing case.

In a slightly different context we also investigated the nonparametric estimation of regression functions. It is reasonable to expect that with a large amount of empirical data we could achieve a good estimate of a regression function. However, with a large amount of data, we may be faced with computational burdens in processing them. Therefore, a recursive method of estimation may seem attractive. Let (X,Y) be an $\mathbb{R}^d \times \mathbb{R}$-valued random vector and let $(X_1,Y_1),\ldots,(X_N,Y_N)$ be a random sample drawn from its distribution. In [11] we considered estimating the regression function

$$m(x) = E\{Y|X=x\}$$

from the data $(X_1,Y_1),\ldots,(X_N,Y_N)$, and we presented a recursive version of the nearest neighbor regression function estimate. This estimate retained the flavor of the nearest neighbor estimates, but the processing burden arising from the ranking procedure was less. Distribution-free convergence results were presented. Also in [11], an application to the discrimination problem was considered, and the first distribution-free strong Bayes risk consistency result in the

literature was given.

3. Adaptive Delta Modulation:

This investigation has been concerned with how an adaptive delta modulator (ADM) performs with a stationary Gaussian input X(t). The measure of performance is the limiting average squared error between the input X(t) and its digital approximation Y(t), namely,

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T (Y(t)-X(t))^2 dt. \qquad (1)$$

Assuming that X(t) is Gauss-Markov and making an assumption about the time averages of X(t), Y(t), it was shown that (1) is the same as

$$\lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} (X(nT)-Y(nT))^2 .$$

The impact of this result is that in simulating the adaptive delta modulator, the points X(0), X(t), X(2T),... are the only ones that need to be generated in order to estimate (1). A simulation study revealed that the ADM achieves its best performance for PQ=1 and $1.002<P<1.1$. While this performance is essentially equal to that of the ordinary delta modulator (P=Q=1) with an optimally chosen Δ which depends on T_0 and X(t), the ADM achieves its performance regardless of the initial Δ used, the sampling time T_0, and the distribution of the underlying Gauss-Markov process X(t),([12]).

During the 1981-1982 contract year, Professor Jason L. Speyer is joining the program as a Senior Principal Investigator in this unit. Professor Speyer, a faculty member in the Department of Aerospace Engineering and Engineering Mechanics, is an expert in the areas of estimation, stochastic control, detection, and optimization. Due to the pressure of other committments, Professors T.J. Wagner and G.L. Wise will not be participating in the program during the 1981-1982 contract year. However, the major thrust and objectives of this unit remain the same.

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THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE80-2 ELECTRONIC MULTI-DIMENSIONAL SIGNAL PROCESSING

Principal Investigator: Professor J.K. Aggarwal (471-1369)

Graduate Students: N. Huang, T. Leou and S. Park

A. PROGRESS: The broad objective of the research unit is to develop new techniques for processing multi-dimensional signals. The current research focuses on the analysis, synthesis and implementation of linear shift-variant (LSV) digital filters and the development of efficient techniques to implement two-dimensional (2-D) semicausal recursive digital filters. Linear shift-variant digital filters have been found desirable in many applications such as geophysics, communication systems, speech analysis and synthesis [1]. Recently, considerable attention has been directed toward various aspects of filters with variable parameters. Our approach is to examine linear shift-variant digital filters in both time and frequency domains.

We have developed a framework for the analysis and synthesis of LSV digital filters in frequency domain [2], [3]. Our approach involves the notions of the short-time spectrum and the generalized frequency function. The short-time spectrum is a useful measure of the frequency content of nonstationary sequences. In our research, we are interested in being able to modify the short-time spectrum using an LSV digital filter. We first analyze the desired nonstationary sequence in terms of its short-time spectrum. Then the generalized frequency function of the LSV digital filter is specified from the short-time spectrum. The proposed technique allows the spectral modification to be a function of time and thus vary with the changing frequency content of the desired sequence. The overall advantage is that the resultant bandwidth of the shift-variant digital filter is much narrower than that of the linear shift-invariant (LSI) filter. Consequently, the LSV filter can remove more undesirable frequency components to obtain better results. With this technique, we also explore an implementation procedure which allows the outputs of LSV digital filters to be computed from those of LSI filters by using an interpolating scheme. The performance of the LSI digital filter is evaluated by a simulation program. The results demonstrate that our spectral technique for the shift-variant filtering process is promising and significant [4].

In [5], [6], we present three characterizations of linear shift-variant digital filters; i.e., the impulse

response, the generalized transfer functions and the shift-variant difference equation. We derive the interrelationships among these characterizations. Specifically, we have proven that an impulse response is realizable as a recursive shift-variant difference equation if and only if it is a degenerate sequence. A degenerate sequence is the one that can be expressed as a sum of a finite number of products of two sequences, each of which is a function of a single integer variable. From the properties of the impulse response of a shift-variant difference equation, we have derived in [5], [6] the relationship between the class of filters characterized by rational generalized transfer function and the class of filters characterized by shift-variant difference equations. This result clarifies the problem of attempting to define the concept of nonstationary poles for shift-variant digital filters.

The use of semicausal or half-plane filters in image processing generally requires a large amount of extra grid points to produce the output image compared with the case of employing a causal or a quarter-plane filter. This is inherent in the nature of semicausal filters. In [7], we investigate this problem and present a method to reduce the size of the output frame. This is done by augmenting the input image with the state-control signal which prohibits propagation of the state vector beyond the prescribed frame. Our implementation technique is very desirable from the practical standpoint since it provides a means to get an output image without computing the states outside the prescribed rectangular frame which is of little interest, although it introduces some noise in the output image.

This report is a brief summary of our accomplishments conducted under the Joint Services Electronics Program in the past year. The present research efforts on multi-dimensional signal processing will be continued. Specifically, problems associated with the synthesis and implementation of recursive linear shift-variant digital filters will be explored. In addition, we propose to establish certain relationships between one-dimensional linear shift-variant digital filters and two-dimensional linear shift-invariant digital filters. Preliminary results have been prepared for presentation and publication at International Symposium on Circuits and Systems to be held in Chicago.

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II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE 80-1 INTERFACE REACTIONS, INSTABILITIES AND TRANSPORT

Principal Investigators: Professor M.F. Becker (471-3628)
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Graduate Students: S. Chao, K. Chen, L. Lancaster, G. Lee, D. Sheng, S. Park, and J. Ambrose.

A. RESEARCH OBJECTIVES: The overall objective of this research is to expand on our understanding of fundamental processes at the interfaces of electronic structures. The interface structures of interest are contacts and or barriers whose stability determines the overall lifetime and reliability of electronic devices and circuits. The fundamental information gained in these studies is also expected to be potentially useful for synthesizing new and improved electronic devices and materials.

In our previous research we have shown that electronic instabilities may drive the solid phase surface chemical modifications that alter the properties of electronic interface structures. Many surface chemical kinetic paths are available for relieving the instabilities, but the actual path selected may depend upon a large number of experimental parameters and selective chemical kinetic paths cannot generally be predicted. At present out work is being concentrated on (1) understanding the fundamental, and possibly universal origin of the electronic instabilities and (2) experimentally exploring their relaxation in specific important electronic systems.

In the past year our research has been focused on two general problem areas. The first area concerns the general problem of understanding the reaction paths selected by silicon interfaces at low reaction temperatures, i.e., below eutectic and melting points in the equivalent bulk systems. We are particularly interested in the reaction paths for transition metal-silicon interfaces. Progress in several related studies of these systems are reported in the next section. In these studies we have: (1) compared first phase nucleation and reaction paths in metal-semiconductor systems with those in metal-metal systems; (2) begun studies to determine the effect of the variation of the interface structure along the reaction path on the noise and dielectric properties and, conversely, the use of noise and dielectric properties to

determine interface structure; (3) attempted to determine the possible effects of structural symmetry in the selection of a reaction path.

In related studies we have been concerned with the role of native oxidation, surface contamination, and surface order on the reaction path in transition metal-silicon interfacial systems. In one study we have developed a liquid Hg probe technique for monitoring native silicon oxidation and investigation the role of surface resistivity and contamination on the chemical kinetics. We have also been studying the role of interface oxidation and crystalline order on reaction paths in the V/Si system. This system exhibits the full range of anomalies observed in the nucleation sequence of refractory metal silicides and, as such, is regarded as a model system.

Along these same lines we have conducted an ellipsometric investigation of transition metal-silicon interfaces to correlate changes in refractive index with those in surface resistivity. The objective of these studies is to explore the temporal sequence of electronic and lattice events attending the electronic delocalization observed as a precursor to silicide nucleation.

The second area of research concentration is on the nucleation of damage in solids by high fluence, pulsed lasers. Recently we launched a new attack on this problem in which we view the laser-induced processes from the perspective of nonequilibrium phase transitions. This point of view has suggested a new avenue of experimental research aimed at understanding how the laser optical energy is transferred to the lattice of specific materials. At present our understanding of the critical energy transfer is insufficient to guide materials selection, for example, or to assist the synthesis of laser hardened materials or surfaces.

B. PROGRESS: We have determined that in some of the metal-semiconductor solid phase reactions an electronic transition within a noncrystalline state is an important step in the reaction path leading to nucleation. This was seen in some detail in the Co-Si system for Co_2Si as a critical thickness for nucleation on a high resistivity Si substrate and the accelerated nucleation with no critical thickness on degenerately doped substrates [1].

A comparison of metal-metal systems [2] with the metal-semiconductor systems [1,3,4] has indicated, whereas for metal-metal systems where a minimum undercooling (or marginal instability)[5] seems to be the determining factor,

in a metal-semiconductor system we must contend with concentration regions where glass formation is important. This effect produces phase skipping in the metal-semiconductor systems.

Excess $\frac{1}{f}$ noise measurements are currently being made on Co-Si thin films, particularly those around the first nucleation transition. Using sputtering deposition times of 60, 80 and 90 seconds which produce films in the semiconducting, transition, and metallic regions respectively, we have compared the low frequency noise spectra with those of carbon resistors of appropriate resistance. Initial measurements at 30°K indicate an anomalously large $\frac{1}{f}$ noise in the 60 and 80 sec. films as well as anomalous behavior on current at the lower frequencies. We have as yet made no effort to explain this data, but instead are presently concentrating on determining that our experimental procedures are producing consistent data and accumulating a sufficient amount of experimental evidence in order to look for the ramifications of the prenucleation structural changes.

The group theoretical work on the silicide structures is continuing in an effort to determine if symmetry is playing a role in determining the reaction path leading to nucleation. To date, we have not been able to determine that any term (like a 3rd order invariant) is important to drive the solid state reaction. However, certain structures seem to be preferred for nucleation, much as BCC seems to be preferred at the elemental freezing transition [6]. However, the group theoretical interpretation of this is at present unclear.

We are planning on continuing all of this work as all phases show promise of increasing our understanding of the solid phase reactions occuring near room temperature at the interfaces of materials. The comparison of metal-metal and metal-semiconductor systems is being extended to a more microscopic level where we may be able to shed some light on the controversies surrounding the structure of metallic glass as well as to determine some of the reasons for selection of particular reaction paths within a general context.

The measurements (and their interpretation) of excess $\frac{1}{f}$ noise should help us to better understand the properties of structures encountered along the reaction path as well as determine when instabilities are about to set in. In addition to extending our data base on the Co-Si system in terms of various thicknesses, temperature variation and current variation, we plan to begin measurements on other systems (in particular the Ni-Si system) in the immediate future.

Dielectric response measurements have not been begun yet as the best measurement circuit is still under active consideration. The combination of dielectric response measurements and excess noise measurements would seem to hold unusual promise in not only determining the low frequency fluctuations and instabilities present in thin film structure, but also as a test of some of the recent theoretical work on these subjects [7].

The symmetry properties of the nucleated phases are being studied in terms of different planes in the reciprocal lattice. There have been conjectures in the literature that not all of the Landau-Lifshitz rules need be used for "barely-first order" reactions [6] (relaxation of the 3rd order invariant rule) and that not all of the rules may be obeyed for 2 dimensional lattices (also relaxation of the 3rd order invariant rule). In view of the preferential occurrences of certain structures in the first nucleation product it would seem that structure symmetry plays a role in these interfacial first order reactions. Our studies have shown that a selection criteria based entirely on a 3rd order invariant rule is clearly not correct, but such a rule may be correct for the "skipped phases" which are in concentration regions of good glass formers. This work is underway.

Reaction paths on "technical" silicon interfaces, i.e., those prepared by conventional electronic processing techniques, are influenced by surface oxidation and contamination and residual disorder. We are currently investigating the role of these variables in specific systems. We have made progress in (1) developing a new technique for monitoring the native surface oxidation of silicon and (2) exploring the role of interface oxygen and disorder on interfacial compound nucleation in the vanadium/silicon system.

The chemical kinetics of the native oxidation of silicon surfaces at room temperature is an important problem in many areas of technology. Previously, the chemical kinetics of native silicon oxidation had been studied by ellipsometry, AES, ESCA and other spectroscopies [8-11]. Only in ellipsometry can one make inobtrusive, in situ measurements on the growing interface but none can explore correlations between the dynamic electronic properties of the interface and its stability. This requires a technique for probing the electronic transitions directly involved in the surface kinetic processes which, as many theories suggest, may involve elastic or inelastic tunneling. Low temperature chemical processes may also involve many-body processes, with the reaction path selected by some dominant dynamic correlations.

We have studied the use of liquid mercury (ℓ-Hg) contacts in an attempt to inobtrusively probe the dynamic electronic interactions at the interface during the native oxidation of silicon. In the experiments we monitored the changes in the I-V and differentiated I-V curves of ℓ-Hg/Si interfaces during oxidation. Since Hg and Si form an immiscible binary system, the Hg contact serves only as a diffusion barrier for the transport of oxygen to the growing SiO_2/Si interface. Moreover, this transport is not rate-determining as has been established in experiments in which the SiO_2 was observed to grow to a blocking, nontunnelable thickness[2] ($\sim 40^{\circ}$A) over a period of $\sim$4 weeks during which the initial resistance of the ohmic contact increased as $(\text{time})^{1/2}$. We have shown that this observation is consistent with the logarithmic time dependence of interface-controlled native oxidations observed by ellipsometry [12].

These experiments are in an early phase but it is clear that the method has promise as a simple, but powerful tool for studying the native oxidation process. It should be especially useful in systematically exploring the effect of surface disorder and contamination.

Other experiments have shown a remarkable dependence of the early rate of oxidation on the resistivity of the silicon substrate [12]. In this experiment, the rate at which the native oxide grew, or organized, to a nontunnelable thickness decreased by a factor $>10^6$ as the substrate resistivity was changed from 10^{-2} Ω-cm to $\sim$10 Ω-cm. This result suggests that the critical dynamical processes for low temperature oxidation is extremely sensitive to the free electron (or hole) density of the substrate.

In the next period we are planning to extend this work to examine the effect of initial surface preparation, disorder, and the influence of ambient gases. We will also search the differentiated I-V spectrum for indication of specific interfacial electronic transitions.

In a related study we have investigated the effect of interface disorder and oxygen on the nucleation of interface compounds in the V/Si system. In summary, the major concern is to understand the role of these parameters in the planar nucleation of V_3Si and VSi_2. (An analogous set of questions pertain to silicide nucleation in several other refractory metal/Si systems.)

In general, for annealing in the ~ 600-1000°C range, V_3Si forms when amorphous Si substrates are used and oxygen is present at the interface [13-14]. When crystalline or poly-crystalline Si is used, planar VSi_2 forms independent of

the oxygen concentration [15]. V_3Si and VSi_2 mixtures are not observed unless either the Si or V source is depleted during the growth cycle. Multiphase structures are logically expected under these conditions. In all previous cases in which V_3Si was formed on an amorphous Si substrate, V_5Si_3 was also present [15].

In our work we studied, by AES, TEM and TED, the influence of disorder and oxygen contamination on planar nucleation from 100-500 A V films sputtered onto (100) and (111) sputter-cleaned silicon substrates [16].

In summary, the results of our experiments confirmed the principle features of previous work. However, in one set of experiments, TED showed the unambiguous presence of only V_3Si on crystalline silicon. The only detectable difference in the preparation of these films is the selective introduction of interface oxygen during the anneal of a V/thin α-Si/Si system. The oxygen accumulated at the thin (∿50 A) α-Si/Si interface during anneal, but the system was oxygen free (<1% by AES) initially.

This result seems to indicate that the role of the oxygen is to retard the recrystallization of the thin α-Si layer during the anneal. However, since other experiments indicate that an excessively thick α-Si layer leads to bistable nucleation of V_5Si_3 and V_3Si [15], the thickness of the α-Si must be crucial to the single phase nucleation of V_3Si. This work will be continued in the next period in which we will also correlate the electronic properties of the interface with the structural studies.

We have also investigated the large drop in refractive index of the Co-Si glassy layer for correlation with the change in the sign of the temperature coefficient of resistance (TCR). Ellipsometry on a series of Co/Si interfaces [17] for which the equivalent Co deposit differs by only a few monolayers [18], shows that the refractive index drops quite sharply at Co deposits slightly less than the amount necessary to effect the semiconductor-to-metal transition observed with d.c. TCR measurements, which were taken on different parts of the same samples.

Other measurements on the Co/Si interface [1] strongly suggest a local-delocal electronic phase transition as the precursor of Co_2Si nucleation. Assuming such a delocalization, we modeled phenomenologically the optical frequency dielectric function of a set of electron states [2], each with a charge density,

$$\rho(r) = \rho_o e^{-\gamma r} \qquad (1)$$

where γ is a localization parameter and ρ_0 is found by charge normalization. For small displacements, this system behaves like a polarizable harmonic oscillator with complex polarizability

$$\alpha(\omega) = q^2\left\{m\left[\frac{q^2\gamma^3}{12\pi\varepsilon m} - \omega^2 - i\omega\xi\right]\right\}^{-1} \qquad (2)$$

where q is the electron charge, ω the driving angular frequency and ξ is the damping constant for the system. As delocalization occurs, γ decreases by orders of magnitude and this leads to a rapid decrease in the refractive index, if ξ is not too large. According to this model, as γ decreases the refractive index decrease could be expected to appear somewhat before a change in sign of the TCR, since any decrease in γ decreases the refractive index, while delocalization must be virtually complete ($\gamma \approx 0$) to observe metallic conduction d.c.

We have also continued to study laser-induced surface instabilities in solids [19]. Our recent concentration is on characterizing multiple-pulse, large beam area laser damage in silicon from the perspective of non-equilibrium phase transitions [20]. As such, we expected that the iso-intensity damage transformation kinetics in the vicinity of the damage threshold intensity, I_{th} would exhibit the features of a classical nucleation and growth process. Although the statistical nature of the damaging interaction between light and matter has been observed for large area, single pulse damage of transparent media [21], the evolution of damage induced by near threshold multiple pulses has not been previously studied.

In our first experiments, multiple, linearly-polarized, trains of 38psec pulses of 606μm radiation from a Nd:YAG laser were focused on crystalline silicon samples. These were fixed to a translational stage driven by a stepper motor controlled by a logic unit. The latter was triggered after 2^N irradiation pulses so that sequences of damage spots were obtained. Intensities of 0.5 to 20 GW/cm^2 were used.

Thin Si samples were irradiated at a 5Hz prf while the transmission of the irradiated sample was monitored by a CW-HeNe laser. In the data analysis, we assumed that the change in transmission of the CW beam is proportional to the fraction of the beam spot that was damaged. The iso-intensity damage kinetics obtained could be fitted to an Avrami equation indicating a nucleation and growth process [22].

In our model of the damage process a "critical" damage nuclei corresponds to a local fluctuation of the excited carrier density above some specific critical value. This idea is compatible, in principle, with either an avalanche, or multiphoton, ionization breakdown process. Embryos with carrier densities less than critical correspond to regressional fluctuations.

The important unresolved question about laser damage is that of determining how the laser energy is transferred to the lattice of the solid. To shed some light on this question for silicon, we have used the experimental method described above to determine which part of the damage process can be described to "nucleation" and which to "growth."

We used SEM to examine the evolution of surface damage morphologies with special attention to small number of pulses of near-critical threshold intensities. Under these conditions, and for linearly polarized laser light, a remarkable one-dimensional spatially coherent, "damage" grating is nucleated [20]. Our SEM studies show that, contrary to existing models, the damage grating is nucleated on the front, rather than the exit, face of the thin sample. Furthermore, we have detected coherent damage features, not only in the direction parallel to the optical electric field, but in the orthogonal direction as well [23].

We have also observed from the earliest detectable coherent features, that the orthogonal interaction is dominant near the critical thereshold [23]. These "nucleation" features could result from the constructive interference of the radiation fields of surface avalanche currents and would therefore support an avalanche breakdown model for 1.06 μm radiation breakdown in silicon. This breakdown would necessarily require multiphoton "pumping", however, because in the absence of hot electron effects, the 10^{-13} electron-phonon relaxation time in silicon is too large to initiate the avalanche.

This work is continuing into the next year in which we will combine damage studies of this type with picosecond optical probe-and-excite measurements in the sub-critical regime. In the latter we will be searching for evidence of damage pre-cursors, i.e., anomalies in the fast optical response to near-damage intensities.

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THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE80-2 SPECTROSCOPIC STUDIES OF METAL/SEMICONDUCTOR AND METAL/METAL OXIDE INTERFACES

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A. OBJECTIVES: The scientific objective of this research unit is to investigate atomic and molecular level properties associated with selected solid surfaces and solid state interfaces. The work is divided into three related subareas: 1) metal/semiconductor interfaces, 2) metal and semiconductor surface/adsorbate systems, and 3) metal/metal oxide systems.

Research on metal/semiconductor interfaces is focused on understanding the electronic structure and composition of silicide structures which form when metal atoms deposited on a semiconductor surface react to form an interface. Particular emphasis is being directed towards understanding the initial stages of interface formation. This work utilizes Auger electron spectroscopy (AES), to characterize near surface composition, low energy electron diffraction (LEED) to determine geometrical structure, angle resolved photoelectron emission spectroscopy (ARPS) to study electronic properties of the constituant atoms, and x-ray photoelectron spectroscopy (XPS) to study the chemical state of silicon and the deposited metal. Additional effort is being directed towards developing a nondestructive means of probing the electronic structure in practical interfaces. This work will utilize optical reflectance to obtain the multilayer dielectric constant associated with a practical interface. The dielectric constant when correlated with results of other experimental techniques such as AES and channeling, should give a reasonably good picture of the electronic structure and composition of practical metal/semiconductor interfaces. Depth-profiling with AES and XPS analysis of these systems will also be employed.

Research on surface/adsorbate systems is primarily oriented towards supporting our work on metal/semiconductor interfaces and on metal/metal oxide interfaces. In preparing any solid state interface, impurity atoms and molecules are incorporated from the background of atomic and molecular species in the vacuum chamber. These impurities can chemisorb at surfaces where interfaces are being formed and can influence the growth kinetics, electronic properties, and crystal structure of the interface. Our research includes investigations of the structure and composition of selected

adsorbates on semiconductor, metal and metal oxide surfaces with emphasis on materials used in interface systems being investigated under metal/semiconductor and metal/metal oxide headings. Several state-of-the-art experimental techniques are available to accomplish this work. These include the capability to measure intensity vs voltage curves for LEED beams and the capability to obtain the vibrational spectra of atoms and molecules at surfaces using high resolution electron energy loss spectroscopy (EELS). These capabilities provide an opportunity to obtain detailed structural information related to species adsorbed at solid surfaces.

Research on metal/metal oxide interfaces is focused on the development of inert overlayer depth profiling and the use of the more traditional sputtering methods as means of studying the topmost atomic layers that form when a clean metal is exposed to oxygen. This work will utilize electron spectroscopy, particularly XPS, to obtain substrate core level intensities. When these measurements are made as a function of the coverage of some inert (chemically non-reactive) overlayer, the resulting substrate attenuations can be analyzed to furnish a near-surface distribution of oxide. This information is of fundamental significance for materials fabrications.

In a related materials area, the fundamental problem of how one metal binds to another is being studied. The techniques include LEED, AES and flash desorption spectroscopy (FDS). From these measurements metal-metal binding energies, ordered metal overlayer structures and electronic structures of metal-metal overlayer systems are being investigated. Such information is crucial in understanding alloying and segregation. From FDS, quantitative values for the heat of desorption can be measured as a function of coverage. LEED provides data on the development of ordered overlayers and AES, when analyzed in detail, provides local chemical bonding information in addition to atomic composition.

B. PROGRESS: This work unit was added to JSEP effective April 1, 1980. During the last year primary progress has been in the area of setting up and testing the specialized research instruments needed to conduct the work and experimenting with sample preparation and target mounts. Progress in each subarea of this unit is summarized below.

1. Metal Semiconductor Interfaces

Our proposed work on $NiSi_2$ and $PdSi_2$ interface formation utilizes Auger electron spectroscopy (AES), photoelectron emission spectroscopy, and optical reflectance. Con-

struction and modification of equipment to be used in this subarea is summarized below with reference to the capability needed to accomplish the stated scientific objectives.

(a) Photoelectron/Auger/Leed Spectrometer

This instrument will be used to study initial formation of metal/semiconductor interfaces, adsorbate structure and oxidation of metal surfaces. The instrument is now complete and in routine operation. Initial experiments utilizing this instrument have clearly demonstrated its unique capabilities. An investigation of the (100) surface of Ni revealed a very narrow peak at the Fermi level in normal emission geometry. Energy resolution of $\sim$40 meV at 4° angular resolution is required to observe this peak which accounts for this peak not being reported in previous investigations. This peak is attributed to a surface state at $\bar{\Gamma}$ in the surface Brillouin zone of Ni (100). Observation of this surface state has important consequences in relation to several fundamental issues pertaining to the electronic and magnetic structure of Ni [1].

(b) Low Temperature Sample Manipulator/Target Mount

Temperature dependent studies of silicide formation in Ni/Si systems have shown that the interface formation is characterized by high reactivity. Compound formation and graded chemical composition of interfaces formed at temperatures as low as 100°K have been reported [2]. At higher temperatures, stochiometric structures including Ni_2Si, NiSi and $NiSi_2$ can be produced. There is some evidence for an abrupt transition (nearly perfect epitaxy) between stoichiometric silicides and the silicon substrate [3] for (100) and (111) faces based on ion channeling, and other evidence which supports an interfacial glassy layer [4].

One of the primary objectives of our research on silicides is to investigate the initial stages of interface formation and interfacial reactivity. This requires a target capable of cooling substrates to $\sim$40°K and heating them to $\sim$1000°K for cleaning and silicide growth. A cold stage manipulator capable of this has now been constructed and tested.

Tests of the cold stage were conducted by investigating the physisorption of xenon gas on the (100) crystal face of tungsten. A temperature range capability of below 40°K and above 1000°K was established which demonstrates our ability to study silicide growth kinetics at low temperature and also apply inert overlayer techniques to diffusion processes at surfaces.

Initial tests of the cold stage manipulator have produced some interesting results. Several theoretical models have been proposed which predict that the $5P_{3/2}$ photoionization line of Xenon on a metal surface will be split [5]. The splitting can be attributed to the surface electric field produced by the substrate or by the induced image charge associated with the photoionization process. Previous experiments have revealed evidence of this effect, but a conclusive experiment has not been carried out. Our experimental data on the W(100)/Xe system has established accurate techniques for measuring xenon coverage based on Auger line shifts and has shown conclusively that crystal field and image dipole splitting of the $5P_{3/2}$ level is much smaller than predicted theoretically [6].

(c) Bulk Silicide Properties

One specific objective of our research on silicides is to study the bulk electronic properties of epitaxially grown silicide crystals. Several groups have reported the ability to grow epitaxially single crystal silicides of $NiSi_2$ on the Si (100) [3,7]. We have recently been able to grow $NiSi_2$ crystals on Si (100) and Si (111) surfaces and have obtained good Laue and LEED patterns which document this capability.

Our next goal is to produce clean $NiSi_2$ crystals in the photoelectron/Auger/LEED spectrometer, either by insitu evaporation or by cleaning some bulk crystals we have already prepared, and begin to study the bulk electronic structure using angle resolved photoelectron emission. Preliminary theoretical bulk band structure for $NiSi_2$ is available in our condensed matter group, and we have recently demonstrated a reasonably good capability to map bulk band structure using resonance lines available in our laboratory. This was accomplished by measuring the bulk band structure and exchange splitting of Fe (110) along the Γ-H-N and N-G-H symmetry lines [8].

(d) Split Beam Optical Reflectometer

This instrument is in the development stage. Its function is to precisely measure $\Delta R/R$, the difference reflectance divided by the reflectance for two targets. One target serves as a reference surface (a clean metal or semiconductor surface for example) and the second target contains an oxide or interface which is to be studied. The difference in reflectance is related to the surface dielectric response which depends on the physical parameters characterizing the

interface, in particular, the depth dependent dielectric function. The objective of this work is to probe nondestructively the interface using optical techniques. The optical system and electronics is complete, the vacuum system is nearly complete, and the manipulator with target mounts is being developed. The reflectometer should be functional in a few more months.

2. Surface Adsorbate Systems

A high resolution electron energy loss spectrometer (EELS) is being set up, primarily under AFOSR sponsorship. Since this instrument will also be utilized to support some work under JSEP sponsorship, the status and capability of this instrument are briefly summarized here.

This is a true state-of-the-art instrument, which incorporates EELS, LEED, AES, and desorption mass spectroscopy capability. The EELS optics achieve 5 meV resolution and permit measurements of atomic and molecular vibrational energies at submonolayer coverages. The LEED system permits IV curves to be obtained for quantitative structural information. The EELS optics are now functioning at a level above specifications (primarily because of the exceptional care we used in our magnetic shielding) and the LEED optics system has been delivered. The major task which remains before this instrument is in full operation is to construct a rather complicated sample manipulator needed to provide access to all target points in the chamber.

3. Metal/Metal Oxide Systems

In developing procedures for analyzing the interfaces of electronic materials it is important to appreciate the kinetics of the growth of such interfaces, how growth can be altered using competing chemical reactions and how electron spectroscopic probes themselves may alter the results. As part of our program on the behavior of oxide layers on metals, we have just completed a study of electron beam damage, due to oxygen ion desorption, on oxided ruthenium surfaces. This work has been accepted for publication [9].

The reaction is characterized by three kinetic regions when Ru(001) is exposed to 100 L of O_2 at 865K and then titrated with H_2 at this or lower temperatures. The first region is a long induction period, the second a rapid reaction region and the third a slow reaction region. The first two of these are sensitive to electron beam effects, i.e., the 3-5 kV and 5-20uA beam used for Auger analysis. In particular, the induction time is dramatically shortened (by as much as a factor of 10) when Auger analysis with a

focussed e-beam is used. We use x-ray photoelectron spectroscopy as a standard which eliminates e-beam damage. This effect is temperature sensitive and disappears as the analysis temperature increases from 500 to 895 K. We attribute this temperature dependence largely to diffusion of oxygen atoms on the surface into the region where the electron beam is depleting them. This is supported by measurements in the absence of H_2 where a lateral concentration gradient is estimated by moving the sample after a lengthy period of e-beam bombardment. The "spot size" is larger for the higher temperatures. These results are indicative of the care which must be taken when electron spectroscopic methods are used to study kinetic phenomena involving surface oxides.

An even more fascinating e-beam effect occurs in the second kinetic region where the reaction rate is very fast. Here there appears to be an electron induced activation of surface oxygen which enhances its reaction with hydrogen. Clearly much more than the stimulated desorption of O^+ is involved.

We have made excellent progress in studies of the Ag/Rh(100) system and our first paper on this subject [10] can be summarized as follows.

The adsorption of Ag on Rh(100) at 300 K is characterized by uniform growth of at least the first two monolayers. The desorption is characterized by two distinct peaks. The lower temperature state shows zero order kinetics and a desorption energy of 67 kcal $mole^{-1}$ while the high temperature state shows first order behavior. The activation energy is slightly coverage dependent. Our data do not allow a unique description but a preexponential factor of 8.9×10^{12} sec^{-1} and an activation energy of $63.2 - 1.5\ \theta_{Ag}$ kcal $mole^{-1}$ is quite satisfactory. AES analysis can be used to establish the Ag coverage over the first monolayer. The initial dissociative sticking coefficient for O_2 is 0.8 at 530 and 680 K on clean Rh(100) while that for N_2O drops from 0.48 to 0.21 over this same interval. The saturation O(KVV) signal from O_2 is twice that observed for N_2O. The LEED patterns at saturation are c(2x2) and p(2x2) for O_2 and N_2O respectively. Simple site blocking models adequately describe the influence of Ag on O_2 and N_2O chemisorption.

C. CURRENT RESEARCH PROGRAM

(i) Metal Semiconductor Interfaces

The Schottky barrier formed at a metal/semiconductor interface is one of the most important building blocks of modern semiconductor technology. The simplest approximation

for a Schottky barrier is based on an abrupt interface between a pure semiconductor crystal and an epitaxial metal layer. However, a practical understanding of Schottky barriers must be based on the actual structure of the metal-semiconductor region [11-19], and in practical devices, the growth mechanisms must be understood in order to tailor parameters for particular applications. Research under this subunit heading (Metal Semiconductor Interfaces) is directed toward obtaining a detailed understanding of the structure, electronic properties and growth kinetics associated with metal semiconductor interfaces.

Recent studies of metal semiconductor interfaces have shown that chemical reactions between the metal and semiconductor at an interface promote formation of an interfacial layer. Silicides of Ni have been studied using photoelectron spectroscopy [14], ion channeling, energy loss spectroscopy [15] and transmission electron microscopy [16]. From these and other experiments, a picture is emerging of the structural and growth properties of metal/semiconductor interfaces: 1) The interfaces tend to be composed of a silicide of given stochiometry ($NiSi_2$ and $PdSi_2$ for example), and this compound formation dominates the microscopic chemistry of interface formation, 2) interface formation seems to be uniform and very little if any evidence indicates significant amorphous transition regions between the Si substrate and the silicide or the silicide and metal and 3) temperature dependence of the interfacial reactivity shows that kinetics plays an important role in growth of the interface. Ordered silicide layers can be grown on the (111) surface of Si [3,7]. The process is not the normal epitaxial process, but involves a reaction of the deposited metal film with the silicon crystal. The high degree of reactivity associated with silicide formation and the tendency of stoichiometric compounds to form suggests that at low coverages, one might expect "two dimensional" features to appear in angle resolved photoelectron emission spectra. These features would characterize the electronic structure of a very thin (one or two unit cells thick) silicide. The formation of a thin silicide ordered layer should be observable using LEED. A specific current objective of our work is therefore to look for ordered silicide formation at very low coverages (1 to 10 A). In this coverage range electron spectroscopy (UPS, AES, XPS and LEED) will be used to characterize electronic structure including binding energy and dispersion of electronic levels and to study structural changes as a function of initial substrate temperature and overlayer thickness prior to annealing. These experiments should lead to a better under-

standing of the initial growth of a silicide interface and should also help to provide additional insight into the possible existance of amorphous layers at silicon-silicide interfaces.

Bulk $NiSi_2$ grown on Si(111) has a CaF_2 structure. The unit cell is small enough that energy band calculations are possible [17]. We will use angle resolved photoelectron emission (with synchrotron radiation and resonance line sources) to obtain E vs. k relations for epitaxial $NiSi_2$ crystals. Our results will be compared with calculations soon to be available [17]. This work will yield a detailed understanding of the ground state electronic properties (valence and charge transfer) associated with $NiSi_2$.

Experimental techniques based on electron spectroscopy are limited to applications involving only the top 10-20 A because of the escape depth for electrons. Therefore less is known about the structure and electronic properties of practical metal/silicon interfaces. Recent backscattering channeling studies have illustrated the utility of these methods to characterize the structure of thicker interfaces [3,7,16]. These techniques are able to probe for non registered atoms and have been used to study the structure and stoichiometry of semiconductor interfaces. To establish a comprehensive model of a practical interface, some electronic structure information is desirable to correlate with the structural information available from channeling.

We will attempt to obtain information related to the electronic structure using optical reflectance techniques. Optical penetration depths are hundreds of angstroms, and the electronic structure is related to the dielectric constant which can be obtained from optical data. There is strong evidence that the silicide interface tends to be uniform except for perhaps 10-20 angstroms at the metal/silicide or semiconductor/silicide junction. Dielectric models of a practical interface will not be too complicated. For example, it should be possible to obtain dielectric constants for a three layer system consisting of a top layer of $NiSi_2$ a thin region which is possible glassy, and a Si substrate.[2] There is evidence based on UPS and AES that stoichiometry variations occur within 10 to 20 A of PdSi interfaces [19]. Similar variations are likely to be observed in NiSi interfaces. We will attempt to correlate the interface models obtained from optical spectroscopy (dielectric constant as a function of depth) with our own studies based on electron spectroscopy, in particular AES depth profile results. Our overall objective will be to determine if optical spectroscopy can provide a nondestructive means of probing interface dielectric properties.

(ii) Surface Adsorbate Systems

Surface adsorbate work does not represent a major thrust of our present JSEP program however, some work in this area is anticipated, mainly in support of our metal semiconductor and metal/metal oxide work. Here, we simply outline some of the adsorbate studies we intend to undertake under JSEP sponsorship.

Oxidation of a surface is preceded by a chemisorbed oxygen layer. In many cases the overlayer of oxygen is ordered, and the ordering can be studied by LEED. In addition, ordered chemisorbed layers result in two-dimensional band structure which can be studied by angle resolved photoelectron emission. Examples of this have been reported recently for oxygen on Al [20] and sulphur on Ni [21]. LEED and angle resolved photo emission studies of ordered chemisorbed systems provide a detailed characterization of the structural and electronic properties of these systems.

We will look for evidence of two-dimensional structure in chemisorbed oxygen on Ni, Pd, Ru and Cu surfaces, and in chemisorbed Ni and Pd on Si surfaces. At coverages comparable to 2-3 monolayers of Ni on Si, we expect to form something resembling an ordered silicide, and should be able to observe evidence of two-dimensional silicide bands and surface and interface states. These measurements can be correlated with computational work based on thin film calculations [17].

(iii) Metal/Metal Oxide and Metal/Metal Systems

The detailed description and understanding of interfaces between metals and metal oxides is an important materials problem in the sense that the growth and extent of such interfaces and layers have a marked effect on electronic properties. Our goal in this portion of the subunit is two-fold: (1) to develop techniques for quantitative surface analysis and depth profiling that are less destructive and capable of higher near-surface resolution than the standard sputtering/ electron spectroscopic methods and (2) to make detailed measurements of the growth kinetics, atomic and electronic structure of metal-metal and metal-metal oxide interfaces.

The former project involves an important question in the investigation of these surfaces and interfaces: What is the distribution of atomic species on a layer-by-layer basis in the first several ($\sim$5) atomic layers of a mixed metal or metal-metal oxide system? The standard technique of argon ion sputtering and AES can give semiquantitation data, and should be used, but its destructive nature often makes the interpretation difficult. Our proposed procedure would be

complementary and would involve deposition at 77 K of NH_3 or some other relatively inert gas onto a surface of interest. The requirements for this deposited material are that it be chemically inert, form multilayers at the deposition temperature and have transitions away from the region of interest [22]. By measuring the attenuation of substrate peaks as a function of overlayer coverage (which we cancalibrate through known doses) and subjecting these to numerical analysis a depth profile of the topmost substrate layers can be developed.

Building on this technique and adding to it the techniques of in situ controlled submonolayer metal deposition, flash desorption, XPS, LEED and AES we intend to investigate such systems as $Al/Pt/O_2$ and $Ag/Ni/N_2O$. Our interest in the Al/Pt systems stems from our experience with oxygen on these two metals. Aluminum forms very stable oxides, while Pt does not. It does however form surface oxygen compounds [23] under conditions where bulk oxides are unstable. We propose to examine in detail submonolayer to multilayer amounts of of Al deposited on single crystal and polycrystalline Pt followed by exposure to either N_2O or O_2. From these measurements a reasonably detailed picture will emerge of what structures are formed and at what rates. In addition the electronic structure and the stability of various atomic structures can be evaluated in detail.

Depth profiling methods can also be used to analyze the growth of metal-silicides such as Ni, Pd and Pt. This work will be pursued in parallel with the work described in section (i).

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III. QUANTUM ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE80-1 NONLINEAR WAVE PHENOMENA

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A. PROGRESS: This research unit is concerned with analytical and experimental studies of nonlinear wave interactions in physical systems. The work may be subdivided into two areas: (1) *nonlinear optics* in the infrared spectral region in molecular gases, and (2) the development of digital time series analysis techniques useful in analyzing and interpreting fluctuation data generated by *nonlinear wave interactions* in various media.

1. *IR Nonlinear Optics:* The overall objective of this continuing research program in nonlinear optics is to study resonant optical nonlinearities in molecules at infrared wavelengths. The experimental studies all employ third harmonic generation (THG) to probe the nonlinear behavior of different classes of molecules. When used with a step tunable CO_2 laser, this experimental technique can be used to determine the magnitude and spectral dependence of the nonlinear susceptibility.

The first class of optical nonlinearity that has been studied is the purely vibrational nonlinearity which is at least approximately triply resonant. The nearly regular spacing of the molecular energy levels makes simultaneous one-, two-, and three-photon near resonances possible. The second class of nonlinearity utilizes only a single two-photon resonance with a vibrational energy level. The main factor governing the spectroscopic structure in this case is the detuning from the two photon resonance at the vibrational energy level.

Specific objectives for the current work are the minimization of the adverse effect of absorption in the nonlinear gas at the fundamental laser frequency. For the case of the triple resonance, this necessitates the use of molecules with large rotational constants and widely spaced vibrational-rotational energy levels. The laser frequency is chosen to lie between one-photon resonances which contribute to absorption. For two-photon resonant molecules, the problem is more simple. Absorptions are due to high J and hot band absorptions from other vibrational minifolds in the molecule. A

solution for this problem should be to lower the temperature of the gas and depopulate the absorbing levels.

The second objective of the current work is to enhance the susceptibility of two-photon resonant molecules by choosing species with an unusually narrow and strong two-photon resonance. Cryogenic temperatures will be used in conjunction with this selection process to further concentrate the molecular population in the resonant levels. A further aid to the selection process is the relation between the nonlinear susceptibility for this two-photon resonant case and the spontaneous Raman scattering cross-section. Preliminary selection of molecules for study is being done on the basis of a large Raman scattering cross-section.

During the past year, our experimental effort has concontrated on the two-photon resonant molecule, CD_4. An energy level diagram is shown in Fig. 1. It has a strong Raman active resonance at 2108.7 cm^{-1}, which is two-photon resonant with the CO_2 laser line P(12) in the 9 micron band at 1053.024 cm^{-1}. As a symmetric molecule, the two photon resonance of CD_4 has only a single narrow Q-branch. Raman scattering data shows this Q-branch to be 15 cm^{-1} in linewidth and to have nearly two times the Raman cross-section as CO, hence one would expect slightly less than four times the THG.

A series of THG experiments [1,2] have been performed on CD_4 at room temperature, exciting with the P(8) to P(16) lines in the 9 micron band of a CO_2 TEA laser. We measured the THG dependence on gas pressure and fundamental laser power for these lines. Due to fundamental absorption at about J=20 on the tail of the ν_4 absorption band, the maximum THG signal occurred at 300 torr pressure. The THG power did have a consistent cubic dependence on fundamental power, indicating that saturation was not present. At lower pressures, a factor of three enhancement in THG was observed compared to CO.

The spectral dependence of the THG, Fig. 2, shows an unexpected feature. The 15 cm^{-1} wide ν_1 resonance is expected to be centered at the P(12) line. The increasing trend at the higher frequencies is not predicted by any strong spectral features in the Raman spectrum of CD_4. Unfortunately P(8) is the high frequency limit for oscillation in our laser on this band of lines and the behavior at higher frequencies could not be studied.

Recent high resolution Raman spectra of CD_4 have been taken by A. Owyoung [3] at Sandia Labs. The data includes part of this region near P(12) but not near P(8). Modeling based on this data is, as a result, incomplete.

These results suggest double benefits to be gained by cooling the gas. First, the high J absorption of the fundamental should decrease dramatically; and second the Raman spectrum in the vicinity of the two-photon resonance should simplify. The result should be higher ultimate conversion efficiency in the first case, and a more easily interpreted THG spectrum, with possibly higher conversion, in the second case.

An experiment has been started to observe degenerate four wave mixing (DFWM) in CD_4 at the same frequency as the THG experiments reported above. The nonlinearity governing DFWM in two photon resonant media is very nearly the same as that for THG. These experiments are expected to provide a check on the unusual spectroscopic behavior of CD_4 observed in the THG experiments.

This work will continue and is also sponsored by grant AFOSR 78-3712.

2. *Nonlinear Wave Interactions:* The objective of this work is to develop digital time series analysis techniques that enable one to properly analyze and accurately interpret experimental fluctuation data associated with nonlinear and/or nonstationary wave phenomena in a variety of media. One of the principal characteristics of any nonlinear system is the introduction of new frequency components, e.g., harmonics and intermodulation products. The "efficiency" with which these new spectral components are generated is given by an interaction or coupling coefficient. In the case of nonlinear systems where one can define an "input" and "output", the "efficiency" with which the new spectral components are generated is described by nonlinear transfer functions. For quadratically nonlinear interactions, the coupling coefficients or transfer functions are two-dimensional functions of frequency. For cubic interactions, the corresponding coupling coefficients or transfer functions are three dimensional functions of frequency. This clearly suggests that higher-order (i.e., multi-dimensional functions of frequency) spectral densities must be utilized to appropriately analyze and interpret fluctuation data associated with nonlinear physical systems. For a quadratically and cubically nonlinear system, the bispectrum $B(\omega_1,\omega_2)$ and the trispectrum $T(\omega_1,\omega_2,\omega_3)$ are the appropriate spectral densities, respectively.

During the past year our research efforts have focused on the following topics: (a) modelling of nonlinear systems in terms of nonlinear transfer functions, with application to radar scattering from nonlinear targets, (b) the

experimental determination of quadratic complex coupling coefficients from the raw time series data, and (c) the development of a digital technique to estimate the joint wavenumber-frequency power spectrum which describes the space-time statistics of the fluctuations.

a. Nonlinear System Modelling in the Frequency Domain: The objective of this continuing effort is to investigate the practical aspects of modelling in the frequency domain the linear and nonlinear relationship between two physical fluctuating quantities $x(t)$ and $y(t)$. Let $x(t)$ denote the "input" and $y(t)$ the "output". Given two experimental observables $x(t)$ and $y(t)$, first one would like to ascertain whether $x(t)$ and $y(t)$ are linearly and/or nonlinearly related. Second, one would like to model the relationship between $X(f)$ and $Y(f)$ (the Fourier transforms of $x(t)$ and $y(t)$, respectively) with aid of a hierarchy of transfer functions. Although modelling in the time-domain has received a great deal of attention in the past several years, we have focused on the frequency domain since one can then relate the features of the model to relevant physical phenomena such as nonlinear wave-wave interactions. Also, the frequency domain approach allows one to generalize the concept of coherency, thus providing the experimentalist with a quantitative measure of the linear, quadratic, and cubic nature of the model as a function of frequency.

Assuming that the input is a zero-mean stationary Gaussian process, we have demonstrated in ref. [4] that the nonlinear transfer functions (up to the third order) may be expressed in terms of cross spectral quantities such as cross-power spectra, cross-bispectra, and cross-trispectra. These can be digitally computed, using FFT techniques, directly from the raw time series data characterizing the "input" and "output". In addition, we have extended the concept of coherency which measures the goodness of the nonlinear transfer function model. The goodness of fit is measured by computing the fraction of power present in the actual output (in the frequency interval ω to $\omega + d\omega$) which is accounted for by the model.

A number of man-made objects, which are to be detected by radar, exhibit nonlinear effects which in turn result in new frequency components (such as harmonic and intermodulation frequencies) appearing in the back scattered field. In order to establish a conceptual framework which allows one to characterize scattering from nonlinear objects in a quantitative and systematic way, in ref. [5] we have extended the concepts of nonlinear transfer functions to nonlinear radar cross sec-

tions and modified the radar equation to include the nonlinear features of a scatterer. The general concept of a nonlinear radar cross section possesses the following features: (1) it reduces in the linear limit, to the familiar linear radar cross section, (2) it indicates that due to the nonlinear aspects of the target various frequencies in the incident signal "mix" to yield a variety of new frequencies (including harmonics and intermodulation products) in the scattered signals, (3) it reduces, in the appropriate limit, to the concept of a harmonic radar cross section where it is known that the amount of power scattered from a nonlinear target is a nonlinear function of the incident power.

Future work, based on numerical simulation and experiments, will be devoted to exploring the practicality of applying these concepts to nonlinear scatterers.

b. Experimental Determination of Quadratic Coupling Coefficients: In previous Annual Reports and publications [6,7], we have reported on our attempts to identify and quantify, using digital bispectral analysis, the presence of wave-wave interactions in a fluctuation spectrum. As an example of the wide applicability of these concepts, we mention that these techniques are now being used in an NSF sponsored study of the role of nonlinear wave-wave interactions in the evolution of turbulence in fluids [8].

c. Experimental Determination of the Joint Power Spectrum $P(k,\omega)$: Although this work does not involve nonlinear phenomena per se, it does involve one of the fundamental diagnostic problems involving the physical interpretation of fluctuation phenomena. In order to more completely describe a space-time fluctuation, one needs to estimate the joint wavenumber-frequency power spectrum $P(k,\omega)$ which characterizes the spatial and temporal properties of the fluctuation. We are presently developing a digital method for estimating the joint power spectrum, which requires measurements at only two spatial points for a one dimensional fluctuation. The key idea is to determine the fluctuation power in the joint intervals $(k, k+\Delta k)$ and $(\omega, \omega+\Delta\omega)$, where k and ω denote the wavenumber and frequency, respectively. Specifically, we introduce a quantity called the local wavenumber and frequency spectral density which can be estimated from two spatial samples. It appears that the local wavenumber and frequency spectral density is equivalent to the conventional wavenumber and frequency spectrum when the fluctuation is stationary and homogeneous, and consists of a superposition of wave packets.

One of the characteristics of turbulent fluctuations

involves the fact that it is often not possible to measure a deterministic dispersion relation. In this case, one must resort to a statistical basis. The approach is to compute a "conditional" power spectrum $P(k|\omega)$ by dividing the joint spectrum $P(k,\omega)$ by $P(\omega)$. By computing a conditional expectation and conditional variance, one can estimate the "average" dispersion relation (i.e., the expected value of k for a given ω) and the amount of "turbulent broadening" (i.e., the conditional variance of k for a given ω).

In order to check out our digital procedure, and to gain experience in applying it to actual fluctuation data, we are presently utilizing it to study drift-wave turbulence in an rf-discharge. We wish to emphasize, however, that the technique will be applicable to fluctuation phenomena in solids, liquids, and gases.

This work is continuing. As mentioned previously, related work involving utilization of digital bispectral analysis to measure coupling coefficients is supported by NSF. Digital computation of nonlinear transfer functions will be utilized in an experimental investigation of unsteady aerodynamic influence coefficients throughout the flight envelope, including the transonic range. This study has been approved for funding by the USAF Armament Technology Laboratory.

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CD_4 ENERGY LEVELS

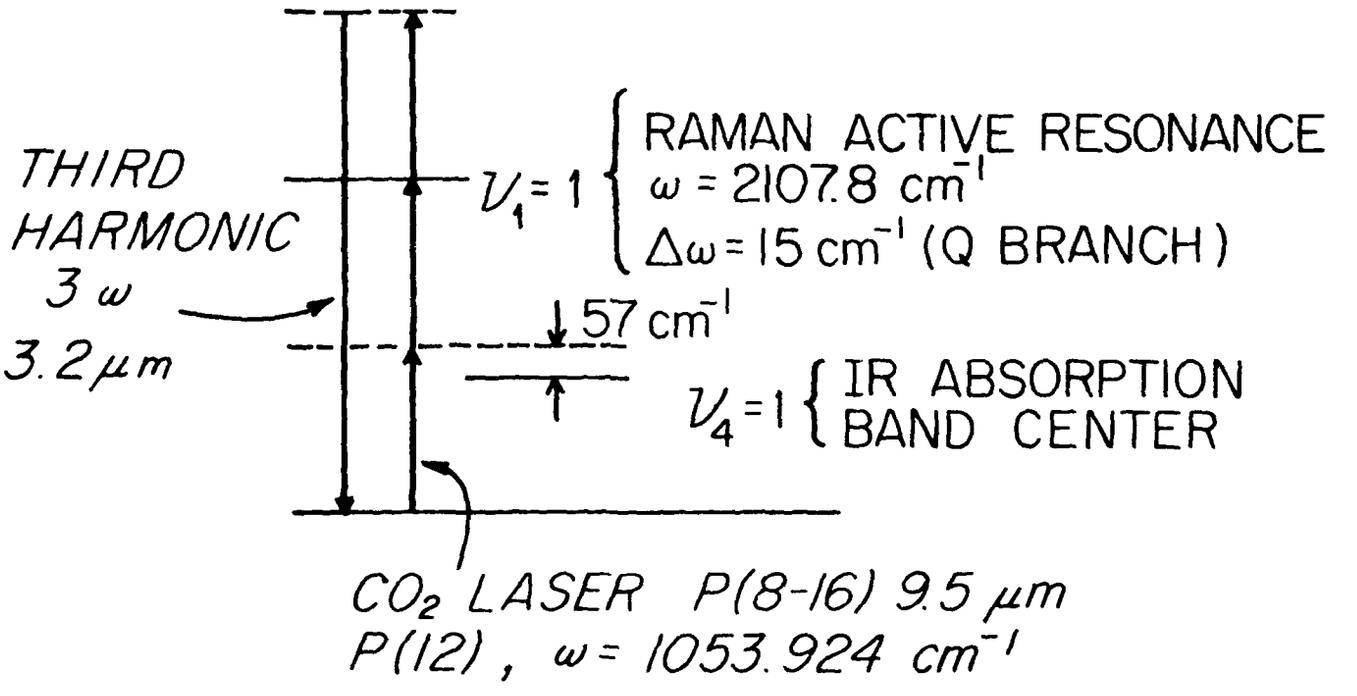

Fig. 1 Energy level diagram of CD_4 showing the ν_1 and the ν_4 modes.

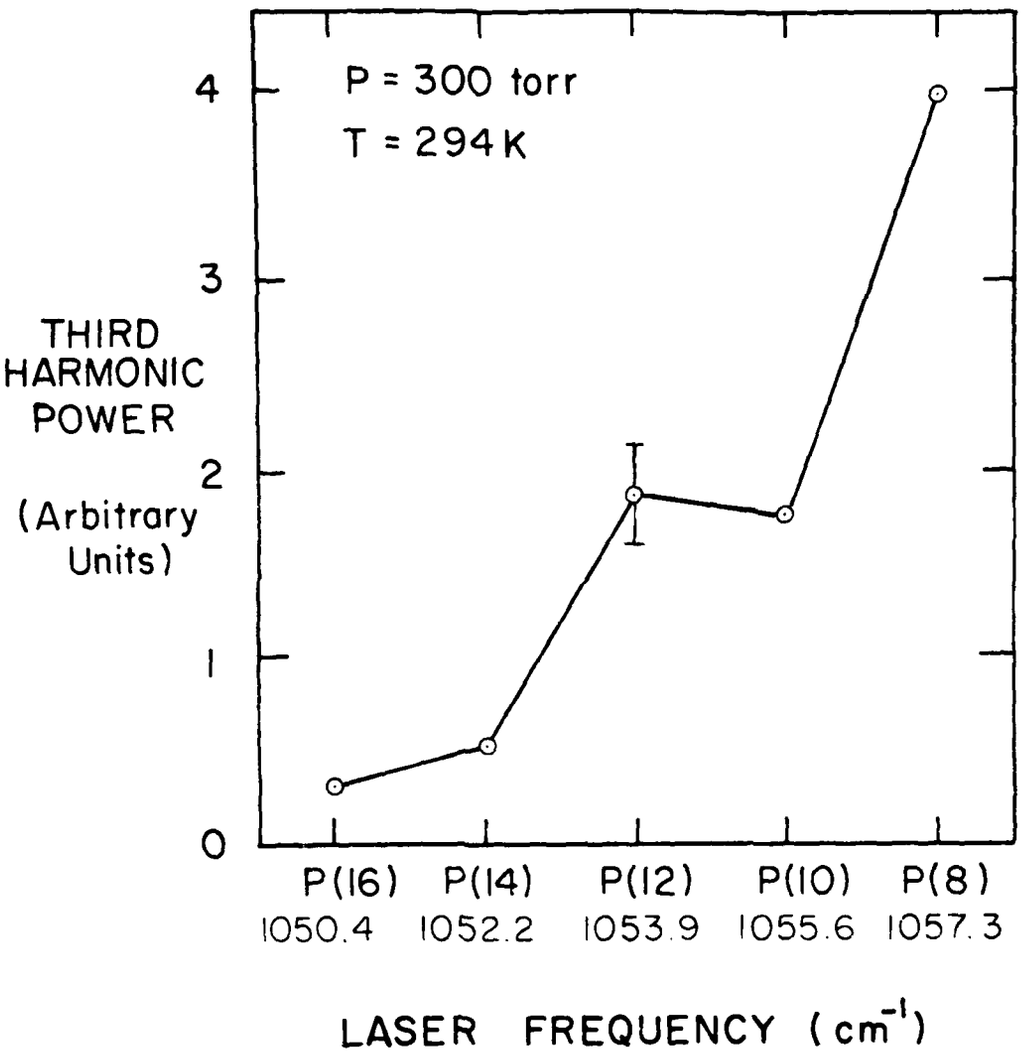

Fig. 2. Spectral dependence of the generated third harmonic power in CD_4. (P numbers on the frequency axis correspond to CO_2 laser lines.)

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE80-2 STRUCTURE AND KINETICS OF EXCITED STATE MOLECULES

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A. RESEARCH OBJECTIVES: These experiments emphasize structural and dynamical studies of molecular systems using non-linear interactions with electromagnetic radiation for detection or for state-selective excitation. The scientific objectives are (1) additional knowledge of the basic process of non-linear interaction of matter with light, (2) development of non-linear techniques as dynamical probes, (3) structural studies of excited states of molecules and ions previously unavailable for study, and (4) studies of energy transfer processes in both collisional and collision-free environments. These objectives will be pursued under three research efforts: non-linear scattering of electromagnetic radiation, inelastic and superelastic scattering of electrons from excited states produced selectively by laser excitation, and dynamical studies of excited molecules produced by multiphoton excitation.

B. PROGRESS:

1. Superelastic scattering. In the study of atoms and molecules by electron scattering, three main processes yield detailed information about the target. Inelastic scattering involves a transfer of a portion of the energy of the incident electron to the target, elastic scattering involves a change in direction of the incident electron without a change in energy, and superelastic scattering involves a transfer of energy from the target (if it is in an excited state) to the scattered electron. In addition, total scattering (inelastic plus elastic) can yield a great deal of information, when used in conjunction with the proper theory. The measurement of these four types of scattering is useful in three energy ranges: low energy, involving 10-1000 eV electrons, medium energy with 1-10keV electrons, and high energy with electrons of energy 30-50 keV. Each energy range has its own area of contribution to knowledge about the molecule or atom in question.

Total scattering at high energy yields detailed information about the molecular structure and the charge density of the target. At high energy, the Born approximation is valid, and a theoretical inelastic scattering can be subtracted from the measured total scattering to yield elastic scattering, from which the charge density or the molecular structure can be calculated. Recently we have been successful in measuring with high precision the charge density in N_2 [1], and also the molecular structure of H_2, D_2 [2], napthalene [3], anthracene, anthraquinone [4], and dimolybdenmum tetraacetate [5], using this method. This work had been supported by JSEP, and is now supported by NSF.

Inelastic scattering at all energies has been known to be a valuable tool in understanding the excited electronic states of atoms and molecules for many years. Pioneering work by Geiger [6] at high energies and Lassetre [7] at low energies has shown the value of this techniques. In the past fifteen years much work has been done in this field, and new techniques have been developed to the point where significant contributions can be made to the understanding of the electronic states of atoms and molecules.

A relatively unexplored field is the counterpart to inelastic scattering, superelastic scattering. Although the electron beam apparatus is exactly the same as that used for inelastic scattering, the necessity of a laser as the excitation source and the extra technological problems of a three beam (electron, gas, and laser) crossed-beam experiment make superelastic scattering a much more difficult process to measure. However, a good deal more information stands to be gained from it. Just as inelastic scattering can determine the selection rules of the transitions from the ground state by observing the angular dependence of the intensities, so can superelastic scattering determine the transitions from the excited state. This gives direct information about the excited state. One can, for example observe the transfer of energy from one excited state multiplet to another via L-S coupling at a Fermi resonance. Also, since the laser is a very monochromatic light source, the high resolving power of optical spectroscopy is realized in the excitation of the specific molecular state. This helps to overcome the resolution limits of ordinary inelastic scattering.

The feasibility of superelastic scattering having been established in experiments using Na, Ba, and O_2 [8,9,10], we have started our investigation of superelastic scattering with the molecules NO_2 and I_2.

A first attempt was made to observe the superelastic

spectrum using a Mollenstedt high energy electron spectrometer constructed by Dr. H.F. Wellenstein and brought to our laboratory while he was visiting for a summer. A high energy gun was installed on a turntable in a vacuum chamber, a gas nozzle was constructed, and the output of a 6 watt continuous Argon ion laser was focused on the region in front of the nozzle. The scattered electrons were energy analyzed in the Mollenstedt spectrometer. Very good high-energy inelastic scattering was obtained; however, superelastic scattering was not observed. From this first attempt, two important things were learned: 1) higher energy electrons are not desirable, since the excitation (or deexcitation) cross section is much smaller than that for low energy electrons and 2) the number of excited states created by the laser is critical for the signal to emerge from the noise. We must have at least 5% excited molecules for the experiment to be feasible.

In order to investigate fully the excitation of NO_2 (and other gases in the future) we have constructed a special vacuum chamber with a nozzle, windows, and a double cold trap system. In this chamber, by monitoring the total fluorescence, we can determine the optimum temperature and pushing pressure for the NO_2 gas, and the maximum laser power before saturation sets in. Furthermore, we can use a tunable dye laser to determine the optimum wavelength for the excitation light. In the event that we find our laser cannot produce sufficient power to saturate the transitions (as will most probably be the case, especially if we use a dye laser), we have been developing a light concentrator, which can enhance the laser power by a factor of 50-100 by repeatedly re-directing the beam into the scattering region. Concentrators have been constructed using elliptical mirrors [11], but we have developed a design which uses spherical mirrors, allowing for ease of alignment and low cost construction.

In parallel with the excitation investigations, a low energy inelastic scattering apparatus has been constructed using a low energy telefocus electron gun and a 127° cylindrical energy analyzer. The inelastic spectrum of air has been obtained with this apparatus, with good intensity and signal to noise ratio. It has been found that the low energy telefocus electron gun has a smaller energy spread than other low energy guns because it maintains a relatively small current density along the beam until it focuses at the desired location. This allows it to avoid a current density dependent anomalous energy broadening, or Boersch effect. The Boersch effect has been the subject of an investigation using the low energy telefocus electron gun, in which a

recent theory by Knauer [12] is applied through computer ray tracing to measurements made of the energy width of the beam produced by the gun [13].

This work will be continued in 1981-82. In the next report we intend to discuss the complete description of the optimum laser excitation configuration for NO_2, and the first attempt at a low energy superelastic electron spectrum.

2. Light Scattering. The emphasis of the light scattering work is on establishing the connection of our measurements with fundamental, molecular theory. The polarized and depolarized Raman spectra of the helium diatoms, $^3He_2$ and $^4He_2$, were obtained recently, the former for the first time. These differ significantly due to the isotopic mass difference, and due to the different symmetries related to nuclear spin (fermion ^3He versus boson ^4He). In spite of these striking differences in the measurements, both polarized and depolarized profiles of the isotope diatoms could be computationally reproduced with our adiabatic, wave mechanical computer code previously described using the same polarizability models as input. This is a requirement of such measurement, because polarizability is an electronic property and does not depend on nuclear spin or mass. An important consistency test of this fundamental, difficult measurement was thus obtained [14, 15].

The depolarized spectra of the isotopic diatoms were shown to be consistent to within a very small uncertainty of 1-2% with a very accurate ab initio calculation [16] of the anisotropy of the diatom polarizability. This work [16] must be considered state-of-the-art; it was done for the first time at the configuration interation (C.I.) level, whereas earlier work, which was seen to be in less precise agreement with our measurements [22], was undertaken only at the self-consistent field (SCF) level, at which electron correlation is neglected. The very small remaining differences between the fundamental theory and the anisotropy model, which is consistent with the observed depolarized spectra, are probably entirely due to dynamic effects: the ab initio data are obtained at zero frequency, whereas our measurement was done with the green line (5145 Å) of an argon ion laser. A most satisfactory agreement with the fundamental theory is thus observed.

The polarized helium diatom spectra, however, indicate that the ab initio trace of the polarizability is still in error by about 25%. This surprising result can be understood when one remembers that the trace amounts to only 1% or so of the anisotropy at the significant separations near the

root of the interaction potential. So, if the anisotropy is obtained with a numerical precision of three significant figures, the trace might still be wrong by 50%. The diatom trace, which is difficult to measure, appears to be even more difficult to calculate from first principles. Independent measurements of the second virial dielectric coefficient appear to support the above conclusion [14,15].

An extremely detailed, complex computation of the neon diatom polarizability invariants, which to a limited extent ($\leq$ 155,000 configurations) includes electron correlation, was recently reported [17]. We were able to compare this remarkable ab initio work with our recent measurement in neon. Again, the anisotropy was seen to be consistent within 2% with our spectra obtained previously [18]; the small differences are most likely due to dynamical effects. The trace is somewhat less accurate as was seen in helium above. A detailed comparison of the fundamental theory with our measurement is in preparation [19]. Apart from providing a most desirable testing ground of such ab initio computational data, our work is thought to be significant as a direct measurement of the distortion of electronic wavefunctions during a collisional encounter.

For the diatoms of the other rare gases (Ar,Kr,Xe) the polarized spectra were seen for the first time [15]. The empirical models of diatom trace and anisotropy is all that is known for these cases, because ab initio computations of sufficient accuracy were not undertaken for any of these gases. Nevertheless, for the argon diatom, the consistency of our trace model with independent measurements of the second dielectric virial coefficient is observed [15,20].

After twelve years of uncertainty, a long-standing argument concerning the absolute intensities of collision-induced light scattering could be resolved. Agreement to within 3% or so is now obtained among the three major groups concerned with such measurement. Argon intensities serve now as a calibration standard for all the other gases [21].

Finally, the computer codes used for the evaluation of collision-induced scattering [22] (CIS) could be modified to also account for collision-induced absorption (CIA). Collision-induced absorption was first observed by Kiss and Welsh [23]. We use as input the ab initio collision-induced dipole moments obtained by Byers Brown and coworkers [24,25] to compute from the adiabatic, wave mechanical theory spectral profiles for direct comparison with the measurements [26]. Whereas in most cases a most satisfactory agreement is observed, for neon-argon mixtures a substantial inconsist-

ency was seen, but not yet understood. More work is required to shed light on this serious inconsistency, which seems to affect all mixtures with neon [27].

Summarizing, it is seen that our work concerning CIS of the monatomic gases has come to its conclusion. Two major review articles describe our efforts in this field [15, 22]. The related CIA study [27] of rare gas mixtures provided an interesting extension of our goals and is also considered complete at this time. Currently, our new measurements concerning simple molecular gases are being evaluated and will be compared with the fundamental theory, while preparations are being made to measure certain non-linear properties of collisional pairs of atoms and molecules.

3. Energy Transfer Reactions. Previous studies of energy transfer in rare gases have been conducted using electron impact excitation [28,29,30,31] as a means of depositing energy. This method suffers from a lack of selectivity. Some other excitation mechanisms that have been used are discharge combined with single-photon excitation [32,33] and single-photon excitation [34]. The discharge method is restricted to pressures below 20 Torr. The use of single photon absorption is limited to transitions with $\Delta J = \pm 1$.

The use of two photon absorption as a means of selective excitation [35] offers several advantages over the other excitation techniques. This method can be very selective if narrow band lasers are used. Indeed, Doppler free spectroscopy can be conducted to reveal very fine detail in the absorption profile. Many states can be accessed via two photon absorption since transitions of $\Delta J=0,\pm1,\pm2$ are allowed; and in addition, with the high power lasers currently available even the "forbidden" $\Delta J=\pm3$ may be excited. There is no limit on the pressure range for the sample; even liquid and solid phase can be studied.

The use of state selective excitation in the measurement of energy transfer rates results in much simplification of the data analysis and minimal computer modelling. The fluorescence from the excited state and states populated by collisions is used to monitor the transfer rates. A time integrated approach has been used in this laboratory. This method consists of using the ratio of the integrated intensities of each of the fluorescent states to that of the excited state. An alternate method utilizes fast electronics and a fast pulse laser to measure the time dependence of the fluorescent intensities directly.

This research group has concerned itself with the study of the collisional processes in Xenon following state

selective photoexcitation to the 6p manifold. The time integrated method was used to analyze the fluorescence produced by two photon excitation by a nitrogen-laser-pumped dye laser. In spite of the broad line width, 20 GHz, some promising kinetic and structural features have been revealed. Fig. 1 shows the fluorescence spectra near 8282A produced by excitation of $2P_5$ at various pressures. At low pressures, energy disposal is primarily via photoemission and some radiationless quenching by ground state atoms [31]. At higher pressures, mixing within the manifold starts to populate several other states in the same manifold. A comparison of the integrated fluorescence intensities from all populated states enables us to determine the degree of mixing and other deactivation processes. Excitation spectra were also obtained by scanning the laser while monitoring a single fluorescence line. At a pressure of 10,000 Torr a double peak line profile was recorded. This is an indication of molecular formation. The peaks were 25 cm^{-1} apart and have been tentatively attributed to vibrational states in the excited molecules.

Recent efforts have been directed toward improving the laser system. The frequency stability has been improved by narrowing the linewidth of the laser such that only one or two cavity modes can oscillate. Computer control of the laser frequency was likewise implemented. These modifications to the laser were initiated to improve the statistics of the experiment as well as to allow for the precise determination of the line profiles even at moderately low pressures. A laser linewidth of 750 MHz has been achieved. The laser frequency is resettable to within 1.4 GHz.

It should be noted that with the use of such a high power laser (>100 watts of ultraviolet radiation in a 5 nanosecond pulse) a large flux of photons reaches the photodetector. The flux produced is large enough that the slow response time of the photomultiplier makes single photon counting techniques impossible, but small enough to make usual analogue techniques impractical. A detection scheme based on the quantitization of the charge from the photomultiplier is used in the time integrated approach to enable the detection of up to 300 photons per laser pulse.

Figure 2 shows the $2P_5$ to $1S_4$ fluorescence dependence on the laser detuning from $2P_5$ resonant frequency at 10 Torr. Although the composite linewidth of the naturally occurring isotopes is an absolute calibration of the detection system will allow the determination of the two-photon excitation cross-section. The Doppler-free character of

this experiment also enables the detailed analysis of the excitation profile for Xenon at high pressure.

C. FOLLOW-UP: Future work will be directed toward a better understanding of the dynamical properties of the energy transfer processes. A synchronously pumped dye laser of picosecond width used in conjunction with the fast electronics will allow the determination of the time dependent behavior of the atoms or molecules. This method will be used to study high density gases, liquids and solids.

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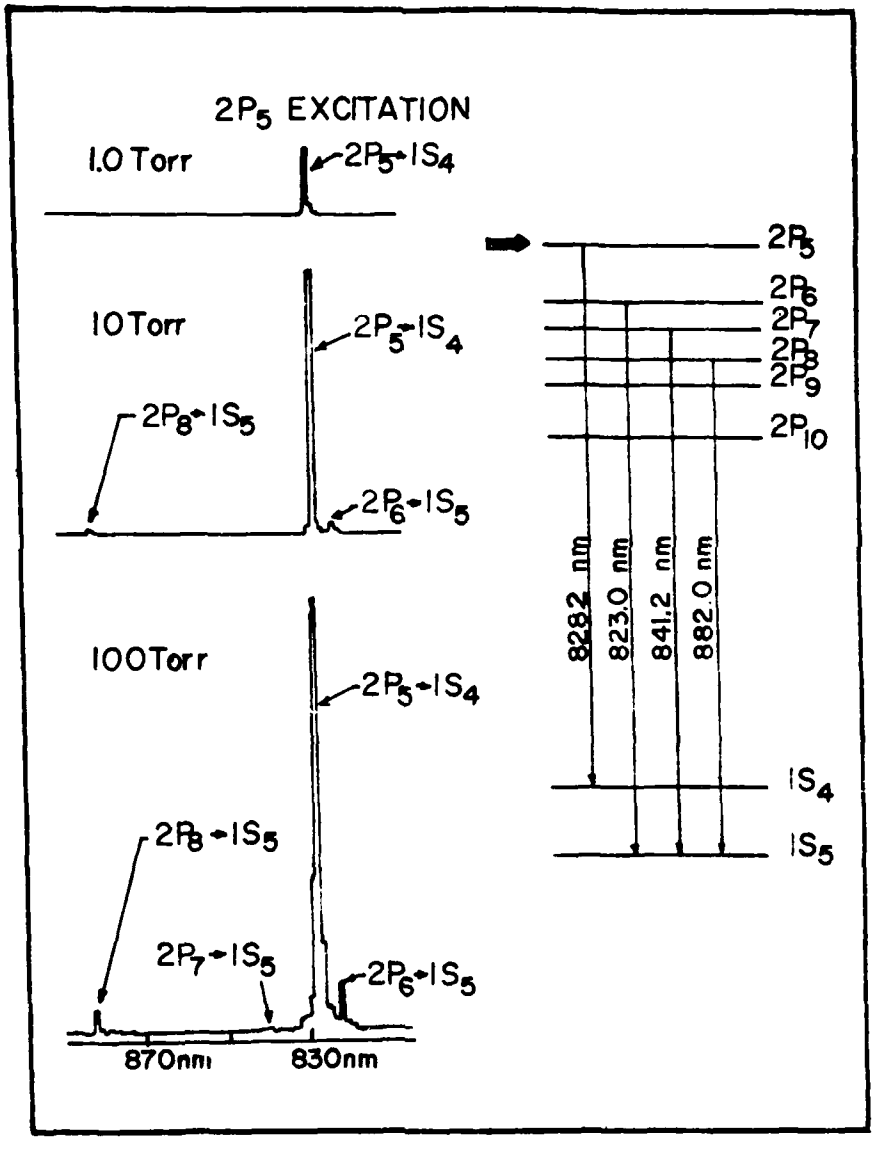

Figure 1.
The fluorescence spectra for different pressures of Xenon following two photon populatin of the $^2P_5$ state. The diagram on the right indicates the fluorescent transtions.

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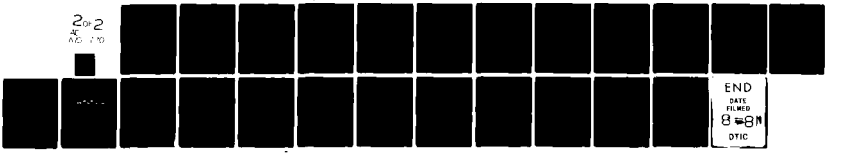

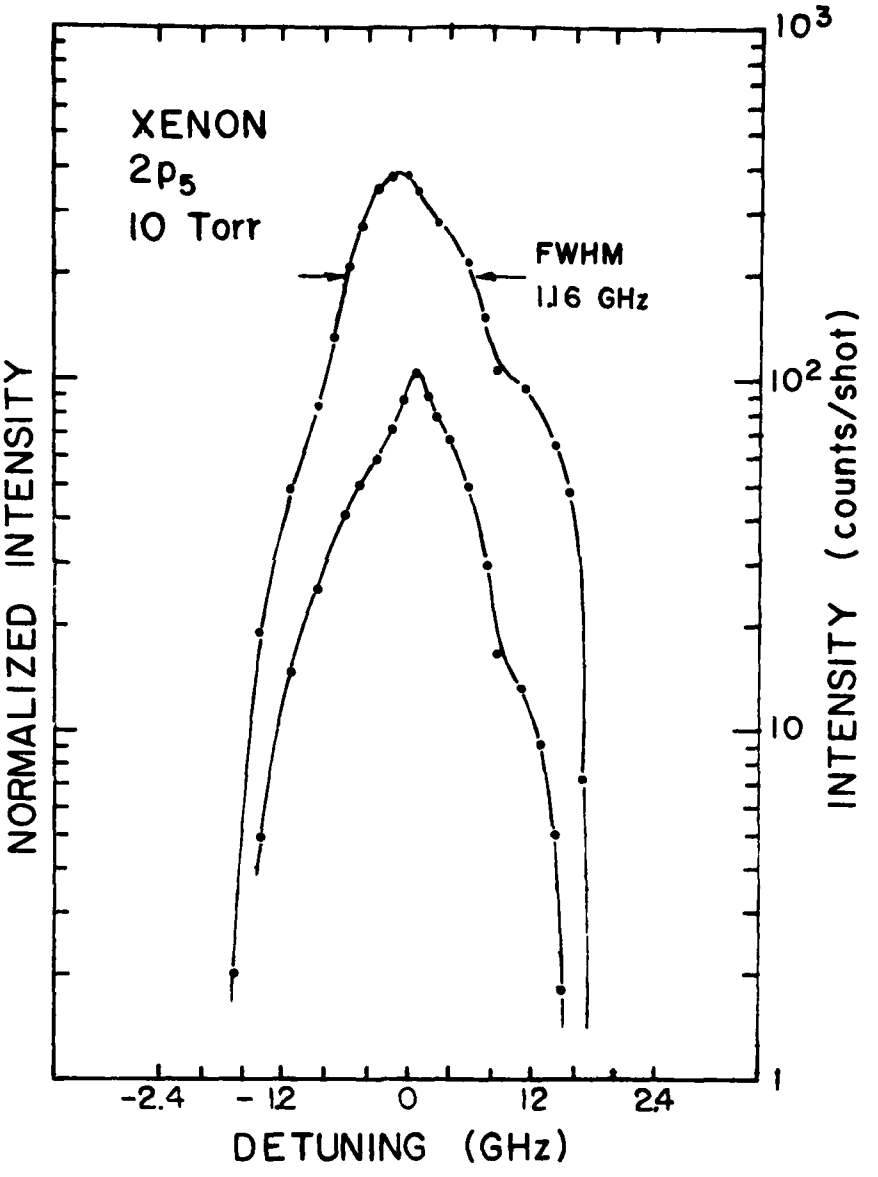

Figure 2.
The lower curve is the fluorescent intensity from $2P_5$ plotted as a function of laser detuning from the two photon resonance. The upper curve is a plot of the fluorescence normalized to the laser power squared.

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE80-3 COLLECTIVE EFFECTS IN NONLINEAR OPTICAL INTERACTIONS

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Graduate Students: P. Alsing, D. Grant, and M. Wolinsky

A. OBJECTIVES: The objective of this research unit is to investigate certain collective aspects of the nonlinear interaction of gas-phase atoms with resonant electromagnetic radiation. Of particular interest in our study is the characterization of the stochastic nature of the atom-field interaction in the optical domain. The research program is divided into the following two parallel efforts: (1) experiments to study the nonlinear exchange of momentum between atoms (or molecules) and resonant electromagnetic radiation and (2) experiments to investigate the cooperative nature of resonance fluorescence in optical bistability. The focus of attention in both areas is the contribution to macroscopic phenomena made by the microscopic fluctuations inherent in quantum mechanical systems. On the one hand, in the study of momentum transfer these fluctuations ultimately limit one's ability to precisely control atomic trajectories by radiation forces, while on the other hand, the quantum nature of the field in optical bistability sets fundamental bounds on the size and stability of optical memories, switches, etc.

The experiments related to momentum transfer in resonance fluorescence have two primary goals. The first is to investigate the dynamical nature of the exchange of momentum between gas phase atoms and resonant electromagnetic radiation. If the absorption of photons is from a directed source such as a laser, there will be a net momentum transfer from the field to the atom over the course of many absorption-emission events, since the emission of photons leaves the atom with zero average momentum. The net gain or loss of atomic momentum can result in significant heating or cooling, perhaps to temperatures below 10^{-3}K [1-4]. While it is possible to set general limits on the heating or cooling process, much remains to be learned about the detailed nature of the time evolution of the momentum distribution.

To study the cooling process, we plan to illuminate an atomic beam with a counter-propagating laser beam. Over the course of the interaction the velocity distribution of the atomic beam should narrow as atoms lose kinetic energy to the radiated field [5]. By recording the time evolution of the Doppler-broadened absorption spectra of the resonance

fluorescence, we will have access to the evolution of both the transverse and longitudinal velocity distributions of the atomic beam.

The second phase of our study of momentum transfer will attempt to characterize the induced-dipole force that results from the coupling of a laser-induced dipole moment (of an atom) to spatial gradients in the driving field. The experiment that we propose follows the recent suggestion by Bernhardt and Shore [6]. A beam of atomic sodium will pass through the standing-wave field of a resonant Fabry-Perot cavity. The resulting deflections of the atomic beam can be much larger than those expected from resonant radiation pressure and are due to coherent momentum exchange between the atom and field.

With regard to our investigation of optical bistability, the emphasis will be on the cooperative behavior of atoms in a nonlinear interaction with the electromagnetic field. This interaction gives rise to the nonequilibrium analog of a first order phase transition. An investigation of optical bistability affords an opportunity to extend the study of the atom-field interaction to include cooperative atomic effects, as well as propagation and boundary conditions for the electromagnetic field. However, in spite of the rather advanced stage of the theoretical development, no experiments have yet been performed to study the statistical properties of the radiation from a bistable cavity.

We propose to study the fluctuation and relaxation processes in optical bistability by observing the spectral density of the scattered field for a Fabry-Perot cavity filled with low density sodium vapor (in the form of an atomic beam), driven by a cw-dye laser. In the region of bistable operation the spectral density should display rather striking features [7,8]. As the turning points of the hysteresis curve of the output versus input field are approached, the spectrum of the fluorescent light narrows to a delta function as a result of a critical slowing down of the fluctuations of the system. As the turning point is passed, the spectrum changes discontinuously into a broad function characteristic of a new "phase" for the atomic cooperativity. Our investigation of the spectral density will use conventional techniques, as in the study of single-atom resonance fluorescence [9].

B. PROGRESS: The past year has been spent designing, modifying and constructing the various pieces of apparatus required for my JSEP sponsored investigations of momentum transfer in resonance fluorescence and of optical bistability.

An atomic beam of sodium has been produced in a newly fabricated vacuum chamber. This atomic beam is excited by the resonant radiation from two different dye lasers, both of which my students and I have installed in the past year. One dye laser provides optical pumping of the atomic beam and serves as a frequency standard in the experiments. The second laser system consists of a ring dye laser driven by a large-frame argon-ion pump laser. The approximately ten-fold increase in output power of the ring dye laser relative to conventional standing-wave lasers is needed to saturate the entire Doppler distribution in our investigations of momentum transfer. The frequencies of these lasers have been successfully locked with feedback electronics to the narrow, Doppler-free linewidth of the atomic beam. We have greatly improved the frequency stability of the dye lasers (to a few parts in 10^9), so that now the laser performance is acceptable for our experiments.

For detecting deflections of the atomic beam due to radiation-induced forces, we have built a Langmuir-type surface ionization detector, which is currently being tested. To study the dynamical nature of resonant radiation pressure, a means of generating time-dependent illuminations over a range from 10^{-8} to 10^{-3} seconds is required. An electrooptic modulator has been obtained for this purpose, and our tests indicate that this device will be suitable for our studies.

Preliminary to our investigations of optical bistability, we have made absolute measurements of the density dependence of the atomic beam as a function of the temperature and pressure of atomic sodium within the source oven. In order to observe optical bistability the single-pass loss in laser intensity through the atomic beam must approach 80%. Such a loss requires a sodium density much larger than that normally obtained from an atomic beam. To achieve such high density we have modified our vacuum apparatus such that five parallel atomic beams provide the needed optical absorption. Absorption spectra of the hyperfine structure of the sodium D_2 line have been recorded in transmission through these atomic beams. An investigation of optical pumping processes within the hyperfine structure is underway. Already we have successfully produced "two-level" atoms by optical pumping and have observed an attenuation coefficient of $\cong 1.5$ in a single pass of the laser through the atomic beam.

We have completed the construction of a resonant Fabry-Perot cavity through which the atomic beams pass. The length of this cavity is stabilized to approximately 10A by using an injected signal from the optical-pumping laser, which is in turn stabilized relative to the narrow absorption pro-

file of the atomic beam.

C. FOLLOW-UP STATEMENT: The lasers, optical components, vacuum system, and associated electronics required for my JSEP sponsored work have been assembled over the past year. Sufficient density in a well-colliminated atomic beam has been obtained to allow us to attempt to observe optical bistability. The first experiment that we will perform in the coming year is a study of the dependence on atomic density of optical bistability. This study should reveal for the first time the critical behavior of the bistability with increasing density.

With regard to momentum transfer, we plan to investigate the time evolution of the momentum distribution of the atomic beam as it is illuminated by a counter-propagating laser beam. The laser intensity will be sufficient to saturate the entire Doppler distribution of the atomic beam so that all atoms will participate in the interaction. Over the course of time, the momentum distribution of the atomic beam should be cooled, perhaps to a level corresponding to a translational temperature of $1^{\circ}K$.

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IV. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM80-1 GUIDED-WAVE DEVICES FOR THE FAR-INFRARED -MM WAVE SPECTRUM

Principal Investigators: Professor A.B. Buckman (471-4893)
Professor T. Itoh (471-1072)

Graduate Students: N. Camilleri, J. Haas, J. Rivera and Y. Shih

A. RESEARCH OBJECTIVES: This work has as its overall objective the identification, analysis and finally, the prototype demonstration of useful semiconductor waveguide devices for production and control of radiation in the frequency range from ten to a few hundred gigahertz. This part of the spectrum is uniquely suited to a number of DoD needs, but its exploitation will require a mix of designs, some using concepts first developed in integrated optics, and other adapting microwave techniques. This research will focus on use of the Gunn and IMPATT mechanisms for radiation sources, and on use of carrier injection and the field effect for electronic active guided wave devices such as modulators, active filters and beam deflectors. For the most part, the device concepts to be studied are compatible with planar waveguide integrated circuit technology.

B. PROGRESS: We have studied gain mechanism in the planar structures shown in Fig. 1 in which the carrier concentration in the n-GaAs layer is so low that no Gunn domain formation takes place along the bias direction between electrodes. A small signal gain accumulates in the wave propagation direction (perpendicular to the plane of the paper). The simplified analysis has been developed based on the flux tube concept. In this approach, the cross section of the device is divided into a number of subsections along the DC flux. It is assumed that the admittance Y_i of each tube per unit length in z is equal to that of the parallel plate structure obtainable by a conformal mapping of that tube. The propagation constant and the characteristic impedance along the z direction are obtained by assembling the admittances calculated in the above mentioned approach for all the flux tubes. The results for the coplanar structure in Fig. 1(a) are

$$\beta^2 = -\frac{j\omega\mu_o b}{2a}\left(\sum_{i=1}^{M} a_i Y_i + j\omega\varepsilon_o \frac{a}{b} + j\omega\varepsilon_s \gamma \frac{a}{b}\right)$$

$$Z_o^2 = \frac{j\omega\mu_o b/a}{8\left(\sum_{i=1}^{M} a_i Y_i + j\omega\varepsilon_o\, a/b + j\omega\varepsilon_s\, \gamma\, a/b\right)}$$

where γ is the effective filling fraction of the semi-insulating region, and a_i and b_i are the effective width and length of the i-th tube. Depending on the bias voltage, β_o has a negative imaginary part which provides positive gain α. A paper based on this analysis as applied to coplanar and microstrip structures will appear in open literature [1]. It was found that the microstrip structure provides more gain while the coplanar structure more stable operation. Some results are given in Fig. 2.

For the experimental part of the work we have continued our efforts to a) get facilities operational for growing doped GaAs epi-layers to specifications determined by our preliminary analyses; and b) obtain some early prototype devices fabriacated elsewhere.

Construction of a metal-organic chemical vapor deposition [2] system is essentially complete, and for the past several months we have been optimizing this system by trying different substrate temperatures, trimethyl-gallium flow rates, and cool-down cycles. The films grown have been investigated for surface topography, crystal quality and chemical composition by scanning electron micrography and energy dispersion spectroscopy.

To within experimental error the films are stoichiometric GaAs (in the absence of dopants). Film thickness uniformity is good within the central two-thirds of the top of the susceptor. We are presently attempting to improve the top surface and crystalline quality of the as-grown films. Scanning electron micrographs reveal a mesa-like epi-layer. However, there are too many valleys to fabricate a device on the as-grown surface. Future efforts will be directed toward achieving sufficient control of crystallinity, surface topography and carrier concentration for fabricating distributed gain devices.

For fabrication of the electrode structures on top of the epi-layers, we are investigating writing patterns in Au by scanning a focused laser beam along a photo-resist coated Au surface. At present the narrowest line width we can achieve is greater than 18 μm. If refinements in exposure and etch technique cannot reduce this line width we in-

tend to reduce it photographically.

We have also obtained outside assistance in fabricating devices. A mask for the co-planar structure was fabricated at Bell Labs, and an attempt made to lift-off the pattern in an electroplated metallization, which was unsuccessful. A Cr mask fabricated at Harry Diamond Labs was used in a lift-off process at Hughes Aircraft on an epi-layer donated by Hughes, but the resulting device suffered from migration induced shorts. A two-step process, described below, will be undertaken next, using a mask aligner-exposer recently received as a gift from Motorola, and at Hughes Aircraft.

Future Directions

1. Extension of Simplified Analysis to Other Structures

Two alternative structures of potential interest are shown in Fig. 3. The film structure is one way to realize a microstrip type configuration discussed earlier. The major problem is its fragileness. For this structure, the analysis is identical to the one developed. The rib structure is more attractive because the major portion of the electromagnetic energy propagates in the rib region and hence the wave is TEM. The analysis of such a structure is simpler than the one provided in the earlier section of this report. We can treat the structure as a uniform line and a one-dimensional analysis is adaptable.

2. Two-Dimensional Analysis

The analysis presented above is only an approximation. Although such an analysis preserves the qualitative nature of the gain mechanism and provides a useful tool in the design process due to short computation time, a more rigorous analysis would be needed if more accuracy is required. Recently, a number of attempts have been reported on the field analysis in various semiconductor devices based on the finite difference or finite element algorithms [3]. It is believed that a finite element approach may be used for the present structure as a two-dimensional analysis. It is expected that the computation time is rather long if reasonable accuracy is required. We plan to study the possibility of using a finite element algorithm.

3. Two-Step Electrode Fabrication Process

To circumvent the problem of migration induced shorts, and to provide the relatively thick electrodes needed to

supply the necessary current, we will employ a two-step left-off process using two masks, as described in Fig. 4. The second metallization is much thicker than the first, but does not approach the GaAs exposed surface too closely. If successful, this process will be employed on epi-layers grown by us or supplied by others, to fabricate and test devices such as those illustrated in Figs. 1 and 3.

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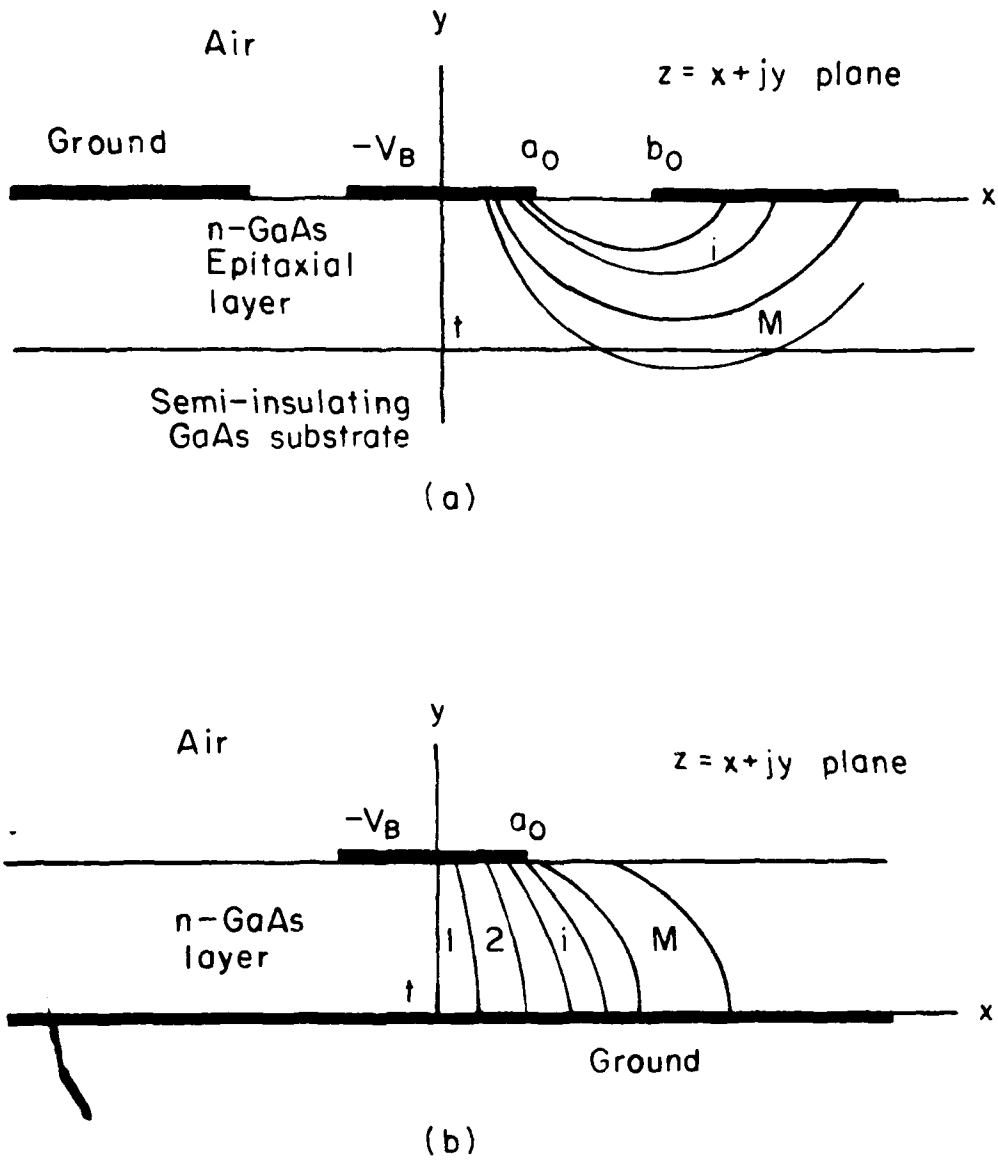

Fig. 1 Structures analyzed (a) Coplanar (b) Microstrip (All contacts are ohmic)

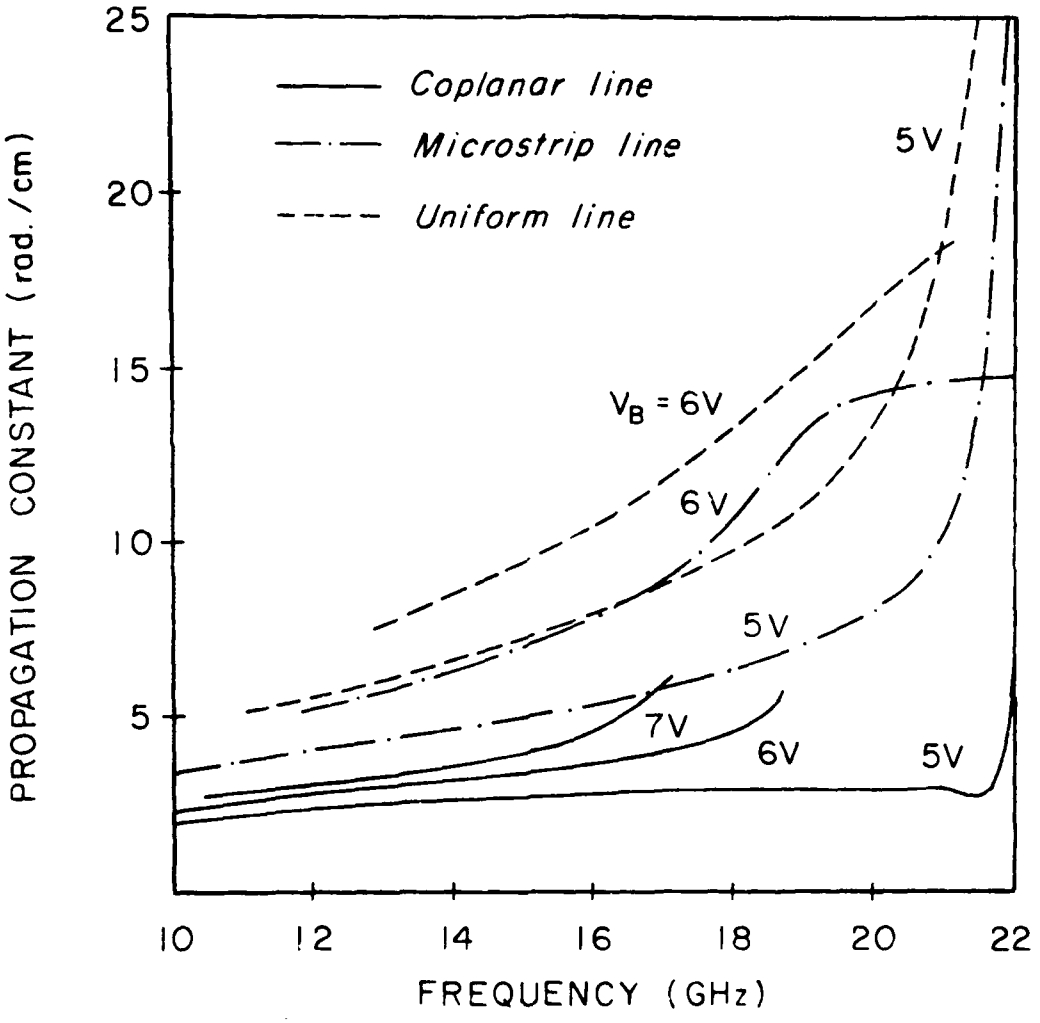

Fig. 2 Frequency-dependent variation of propagation constant when $\alpha > 0$ with doping density $n_o = 10^{15}cm^{-3}$

(a) Coplanar: a_o = 3.5 μm, b_o = 8.5 μm, t = 5 μm

(b) Microstrip: a_o = 3.5 μm, t = 5 μm

(c) Uniform: ℓ = 5 μm

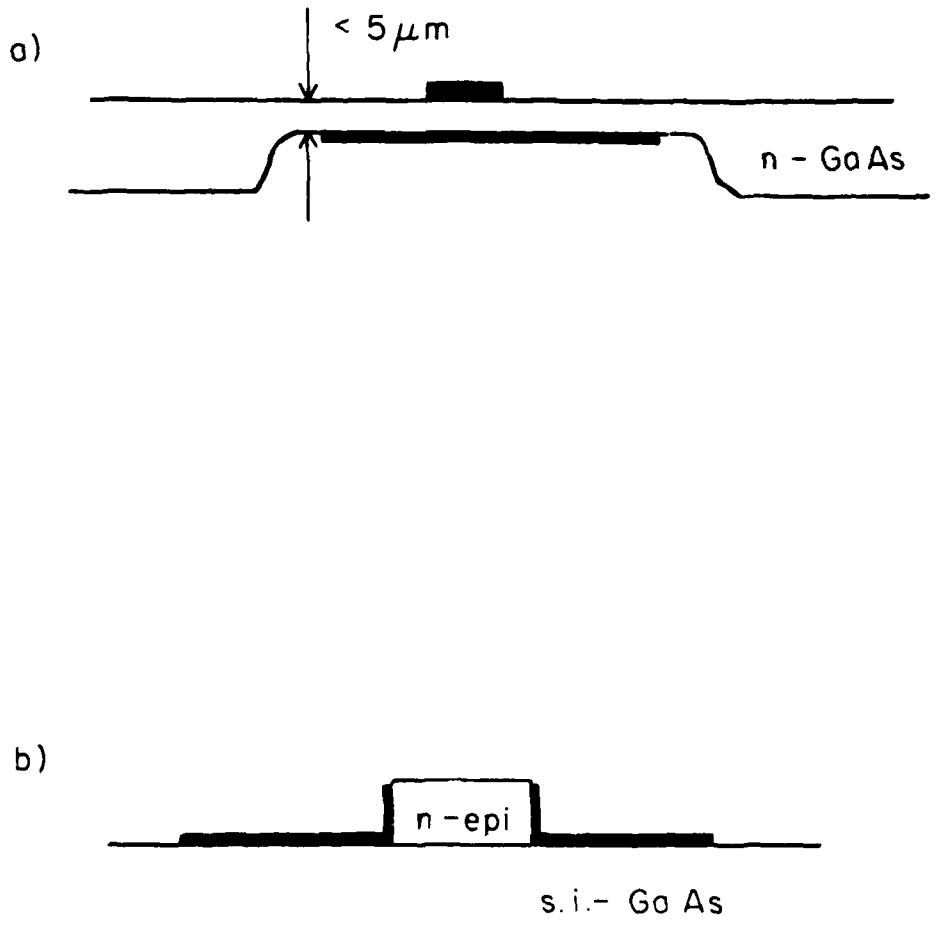

Fig. 3 Alternative structures (a) Film structure

(b) Rib structure

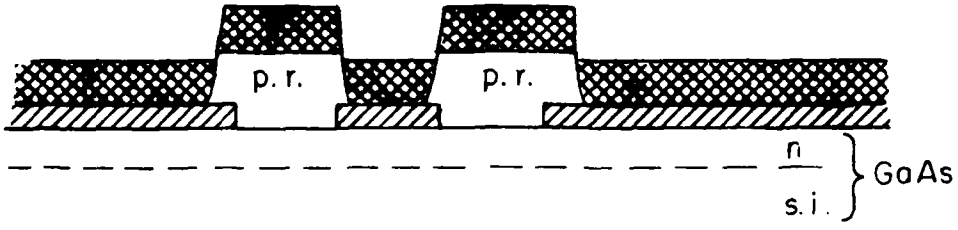

Fig. 4 Two-step electrode fabrication. First metallization shaded. Second metallization cross hatched.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation and (2) electronic multi-dimensional signal processing.

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport and (2) spectro-

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scopic studies of metal/semiconductor and metal/metal oxide interfaces are described.

In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, and (3) collective effects in nonlinear optical interactions.

In the Electromagnetics area progress in guided-wave devices for the far infrared-mm device spectrum is summarized.

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